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Groundwater level trends and aquifer prioritisation in the Murray-Darling Basin

Project RQ8b: Groundwater as an adaptation option to current water resources management

Deliverable T.8b.2

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Executive summary

This report summarises progress in the first year of the MD-WERP Project RQ8b investigating groundwater as an adaptation option to current water resources management in the Murray-Darling Basin (MDB). Groundwater accounts for about 13% of total water use in the MDB. Eight alluvial aquifer systems (equivalent to 19 groundwater Sustainable Diversion Limit (SDL) resource units) account for 75% of the total groundwater use in the Basin. Almost 75% of the groundwater use in these alluvial systems occurs in New South Wales. This report documents the progress of a prioritisation of the groundwater resource units (SDLs) that comprise the main alluvial sequences in the MDB for targeting future studies to improve water management, and an analysis of long-term groundwater level trends in these resource units.

The prioritisation combines an aquifer 'importance' index and an aquifer 'sensitivity index' building on the methods proposed by Currie et al. (2010) and Barron et al. (2011). The aquifer importance index reflects current levels of groundwater extraction, size of the resource, and occurrence of groundwater-dependent ecosystems (GDEs). The aquifer sensitivity index describes the resilience of the aquifer to potential changes in groundwater recharge particularly under climate change. Key updates from previous studies were the incorporation of the latest groundwater extraction data from the Transition Period Water Take Reports (2012-2019), latest estimates of recharge and groundwater resource descriptions, use of the latest GDE Atlas product that enabled ecosystem diversity to be accounted for along with areal extent, and exploration of alternative metrics to account for the relevance of GDE occurrence in the importance index. Regardless of the GDE-related metrics used, the results of the prioritisation were generally consistent for the higher-ranking SDLs and therefore considered robust.

The highest importance indices were obtained for the Goulburn-Murray: Sedimentary Plain (GS8c) and the Shepparton Irrigation Region (GS8a) and the Lower Lachlan Alluvium (GS25) based on the metric used to account for the occurrence of GDEs. The most sensitive alluvial aquifer systems were the Upper Macquarie Alluvium (GS45) given the high recharge-to-storage ratio and average groundwater use close to the SDL. When combining both importance and sensitivity indices, Goulburn-Murray: SIR (GS8a) and Mid-Murrumbidgee Alluvium (GS31) were identified as having both high importance and high sensitivity across different metrics accounting for GDEs. Groundwater footprint metrics as indicators of stress were also calculated as additional lines of evidence. The Lower Namoi Alluvium (GS29), Upper Macquarie Alluvium (GS45) and Upper Namoi Alluvium (GS47), Lower Lachlan Alluvium (GS25) and Lower Murrumbidgee Deep Alluvium (GS28b) were identified as the most stressed SDL resource units.

Methodologically consistent, basin-scale trend analyses of groundwater levels in the main alluvial aquifers of the MDB between 1971-2021 were performed. This analysis was based on robust and widely applied statistical techniques on 910 observation bores that met criteria for inclusion (i.e. at least 2 observations per year, at least 40 years with records, and measuring groundwater level in alluvial deposits only). Results clearly indicated an overall increasing trend of depth-to-water table (DTW) for the MDB alluvial aquifers during the last 50 years (1971–2021), regardless of groundwater level statistics used (i.e., mean, minimum or maximum annual DTW) and trend detection methods used in the analysis (non-parametric Kendall test, linear regression, and two-period comparison). Trend magnitudes ranged from -0.25 to about +1.00 m/year and the 95th percentile was 0.3–0.4 m/year increase in DTW. The largest increases in mean annual DTW were observed in the Lower Gwydir Alluvium (GS24), Lower Murrumbidgee Deep Alluvium (GS28b), Lower Namoi Alluvium (GS29), Mid-Murrumbidgee Alluvium (GS31), Upper Namoi Alluvium (GS47), Upper Condamine Alluvium-CCA (GS64a) and Goulburn-Murray: Sedimentary Plain (GS8c). For the period with reported metered groundwater use data (2012-2019), a moderate positive correlation (r=0.68, p-value=0.008) between groundwater use and increasing trends in mean DTW at SDL scale was detected. It is worth noting that the trend analysis is done at SDL scale and therefore no distinctions are made between shallow and deeper alluvial aquifers. The latter might concentrate important groundwater abstraction rates and therefore trends in groundwater levels might follow specific spatial patterns in deep semi-confined alluvial aquifers. The overall increasing trend in DTW across all alluvial aquifers can be attributable to observed changes (at SDL scale) in diffuse recharge from rainfall and potential evaporation, and groundwater extraction.

When combining aspects related to historical trends in groundwater levels, aquifer importance and sensitivity indices, and metrics of groundwater footprint/stress, 9 SDL resource units are identified as potential priority to improve water management: Lower Gwydir Alluvium (GS24), Lower Murrumbidgee Deep Alluvium (GS28b), Lower Namoi Alluvium (GS29), Mid-Murrumbidgee Alluvium (GS31), Upper Macquarie Alluvium (GS45), Upper Namoi Alluvium (GS47), Upper Condamine Alluvium (CCA) (GS64a), Goulburn-Murray: Shepparton Irrigation Region (GS8a) and Goulburn-Murray: Sedimentary Plain (GS8c). Out of this group, it seems critical to address potential issues related to groundwater sustainability in the Lower and Upper Namoi Alluvium (GS29 and GS47), and in the Mid-Murrumbidgee Alluvium (GS31). Finally, Lower Lachlan Alluvium (GS25) and Lower Murrumbidgee Deep Alluvium (GS28b) are highlighted as high importance–low sensitivity and show signs of groundwater stress when considering aspects of groundwater quality (salinity levels).

1 Introduction

There are 3 one-year activities in Project RQ8b on groundwater as an adaptation option to current water resources management. In Year 1, Activity 8b.1 will improve the understanding of groundwater level trends, groundwater use patterns and priority aquifers to identify where and when groundwater plays a substantial role in the Murray-Darling Basin (MDB), and where groundwater use could be enhanced when used conjunctively with surface water. Building on this, Activity 8b.2 in Year 2 will identify and assess opportunities such as managed aquifer recharge, brackish groundwater desalinisation and deep groundwater bores, for enhancing water supply across priority aquifers. Based on the outcomes of Years 1 and 2, Activity 8b.3 in Year 3 will apply an innovative modelling framework termed Groundwater Commons Game (Castilla-Rho et al., 2019) to integrate and assess social, economic and environmental aspects of conjunctive SW-GW management in a case study considered within the priority alluvial systems identified for the MDB.

The first year of RQ8b aims to provide insights on where the opportunities for enhanced groundwater use are located to benefit economic, social and environmental outcomes in the MDB. The research assesses opportunities to augment water security in key alluvial aquifers where most of the groundwater use takes place. This research aligns directly with the Murray-Darling Basin Authority (MDBA) statement of expectations for managing groundwater (MDBA, 2019), where the role of groundwater supporting rivers, river ecosystems and communities is regarded as critical.

1.1 Scope of RQ8b: Groundwater as an adaptation option to current water resources management

During the first year 2 main activities were addressed in RQ8b: a) characterise spatial and temporal groundwater levels/use in priority alluvial systems of the MDB, and b) apply a prioritisation framework to alluvial systems across the MDB based on aquifer importance, aquifer sensitivity, and groundwater footprint metrics. The project aims to:

- improve the understanding of historical and current trends in groundwater use in alluvial systems across the MDB;
- analyse long-term records of groundwater levels in key alluvial systems and perform factor attribution through trend analyses; and
- identify priority aquifers applying revised concepts of importance/sensitivity indices defined (Currie et al., 2010; Barron et al., 2011), and groundwater footprint (Gleeson et al., 2012; Kourgialas et al., 2018).

Data on groundwater levels are employed to perform statistical trend analysis on aquifer levels of selected aquifers to disentangle factors contributing to these trends. Data on groundwater use, recharge estimates, occurrence of groundwater-dependent ecosystems (GDEs), sustainable diversion limits, and salinity classes are used to prioritise alluvial systems in the MDB through the prioritisation methodology described in Section 3. With these results we will equip the MDBA and stakeholders with updated knowledge to better manage groundwater resources in the MDB.

1.2 Groundwater use across the Murray-Darling Basin

Figure 1 shows the water use across the MDB for the period 2012-13/2018-19 as reported from the Transition Water Take Reports (2012-13/2018-19) (MDBA, 2020b). This data covers the entire Basin use and is considered of high reliability in terms of quality assurance compared to previous reporting (2001-02/2011-12), thus providing valuable insights on total groundwater use. Average groundwater use in the MDB is 1482 GL/y and represents about 13% [8%-18%][1] of the total water use reported in the MDB for the period analysed. Proportional contributions from groundwater to the total available water resources are complementary to surface water resources, and therefore they increase when surface water availability decreases.

MDBA (2020b) highlights that 92% of the total groundwater annual actual take (use) was metered for the year 2018-19, whereas 100% of the groundwater take under basic rights (domestic and stock) is unmetered. This would suggest that recent statistics on groundwater use are more reliable compared to earlier estimates, notwithstanding the lack of metering for groundwater take under basic rights. The latter has been estimated as about 233 GL/y for the period 2015-16/2018-19.

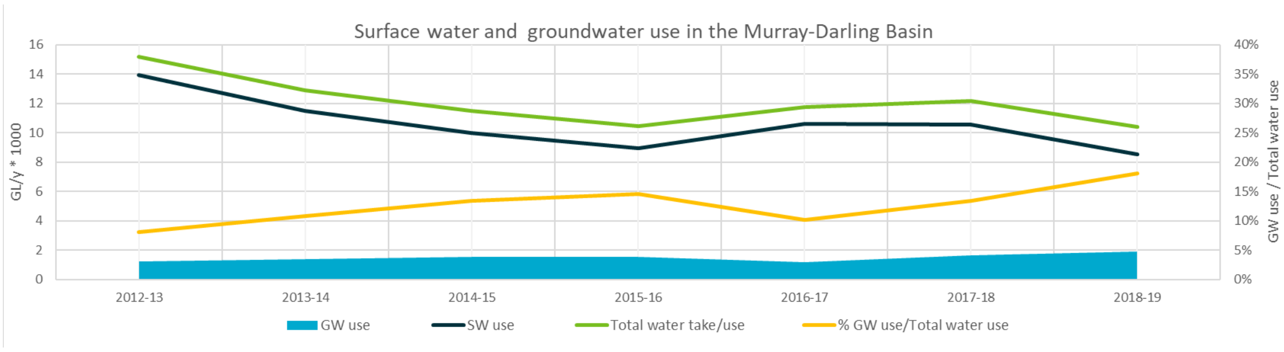

Figure 1 Water use in the Murray-Darling Basin for the period 2012-13/2018-19 as reported in the Transition Period Water Take Reports (2012-2019)

At Basin state level, New South Wales (69%), Queensland (14%) and Victoria (13%) concentrate close to 96% of the total groundwater use reported in the Basin (Figure 2). Most of this groundwater use takes place in large alluvial systems associated with 19 (out of 80) groundwater Sustainable Diversion Limit (SDL) resource units.

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[1] Range = [min – max]

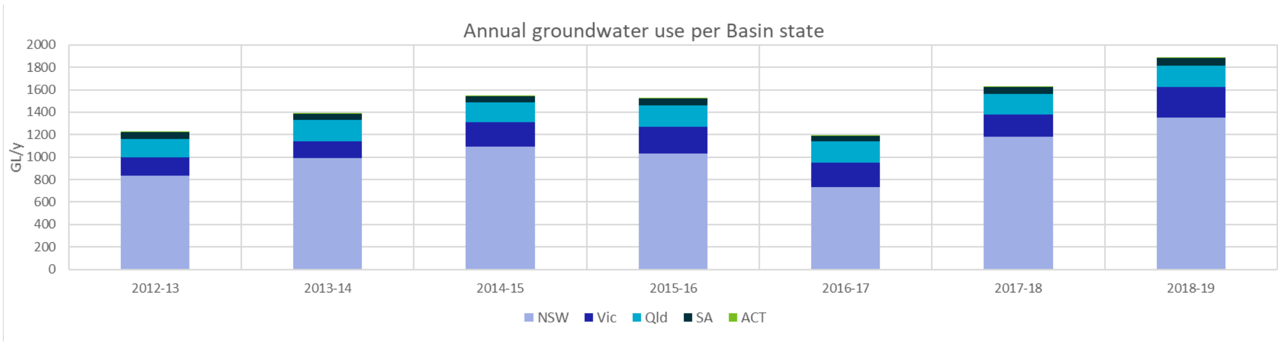

Figure 2 Total groundwater use per Basin State reported for the period 2012-13/2018-19

Most of the groundwater use in the MDB is concentrated in 8 alluvial systems as set out below (Figure 3):

- **Condamine** (Upper Condamine Alluvium – Central GS64a[2], – Tributaries GS64b). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 43% of the total groundwater use metered in SDL resource units of Queensland, with the most recent estimate bringing this value close to 50%. If groundwater use in the Upper Condamine Basalts (GS65) is also included, the average use amounts to 80% of groundwater use in Queensland.
- **Gwydir** (Upper Gwydir, GS43 – Lower Gwydir, GS24). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 4% of the total groundwater use metered in SDL resource units of New South Wales.
- **Namoi** (Upper Namoi, GS47, GS48 – Lower Namoi, GS29). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 18% of the total groundwater use metered in SDL resource units of New South Wales.
- **Macquarie** (Upper Macquarie, GS45 – Lower Macquarie, GS26). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 5% of the total groundwater use metered in SDL resource units of New South Wales.
- **Lachlan** (Upper Lachlan, GS44 – Lower Lachlan, GS25). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 16% of the total groundwater use metered in SDL resource units of New South Wales.
- **Murrumbidgee** (Lower Murrumbidgee Shallow, GS28a – Lower Murrumbidgee Deep, GS28b – Mid-Murrumbidgee, GS31). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 29% of the total groundwater use metered in SDL resource units of New South Wales.
- **Murray** (Lower Murray Shallow, GS27a – Lower Murray Deep, GS27b – Upper Murray, GS46). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 8% of the total groundwater use metered in SDL resource units of New South Wales.

[2] This nomenclature corresponds to the 80 Groundwater Sustainable Diversion Limits (SDL) Resource Units reported by the Murray-Darling Basin Authority (https://data.gov.au/data/dataset/66e3efa7-fb5c-4bd7-9478-74adb6277955. Accessed on 15-November-2021).

- **Goulburn-Murray** (Shepparton Irrigation Region, GS8a – Sedimentary Plain, GS8c). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 88% of the total groundwater use metered in SDL resource units of Victoria, with the most recent estimate bringing this value to 90%.

Reported groundwater use in these SDL resource units comprising these major alluvial aquifers systems in the MDB is presented in Table 1.

Table 1 Metered groundwater annual actual take reported in (MDBA, 2020b)**. BDL: Baseline Diversion Limit and SDL: Sustainable Diversion Limit as defined in Schedule 4 of the Basin Plan**

SDL code	SDL name			Annual actual take (GL/y)							Annual actual take GL/y 2012-2019		
		BDL (GL/y)	SDL (GL/y)	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	Max	Min	Average
GS64a	Upper Condamine Alluvium (Central Condamine Alluvium)	81.4	46.0	32.3	55.1	41.1	42.0	48.0	50.5	57.7	57.7	32.3	46.7
GS64b	Upper Condamine Alluvium (Tributaries)	45.5	40.5	33.9	32.9	30.6	32.6	32.8	33.7	35.6	35.6	30.6	33.2
GS54*	Queensland Border Rivers Alluvium	14.0	14.0	8.85	11.3	11.8	12.8	10.8	14.0	14.4	14.4	8.85	12.0
GS32*	NSW Border Rivers Alluvium	8.40	8.40	2.84	5.59	5.41	3.98	3.38	6.37	8.98	8.98	2.84	5.22
GS33*	NSW Border Rivers Tributary Alluvium	0.41	0.41	0.16	0.17	0.17	0.17	0.17	0.17	0.16	0.17	0.16	0.17
GS27a	Lower Murray Shallow Alluvium	81.9	81.9	2.26	4.10	5.90	5.40	5.97	8.39	11.9	11.9	2.26	6.27
GS27b	Lower Murray Deep Alluvium	88.9	88.9	56.2	45.2	67.5	85.5	36.7	78.9	110.7	110.7	36.7	68.7
GS46	Upper Murray Alluvium	14.1	14.1	12.3	10.7	9.87	11.2	8.66	14.0	17.8	17.8	8.66	12.1
GS28a	Lower Murrumbidgee Shallow Alluvium	26.9	26.9	5.25	6.47	7.15	6.21	6.47	8.17	8.32	8.32	5.25	6.86
GS28b	Lower Murrumbidgee Deep Alluvium	273.6	273.6	179.6	230.3	300.3	268.5	151.5	323.1	377.9	377.9	151.5	261.6
GS31	Mid-Murrumbidgee Alluvium	53.5	53.5	35.5	36.1	40.1	32.4	30.3	42.7	55.6	55.6	30.3	39.0
GS25	Lower Lachlan Alluvium	123.4	117.0	87.2	104.9	120.5	97.5	91.4	127.2	131.8	131.8	87.2	108.6
GS44	Upper Lachlan Alluvium	94.2	94.2	44.2	42.3	57.2	55.7	37.9	75.4	89.4	89.4	37.9	57.4
GS26	Lower Macquarie Alluvium	70.7	70.7	26.9	29.7	32.0	35.2	18.6	40.8	47.4	47.4	18.6	32.9
GS45	Upper Macquarie Alluvium	17.9	17.9	13.7	14.1	15.3	15.9	13.5	21.0	23.0	23.0	13.5	16.6
GS29	Lower Namoi Alluvium	88.3	88.3	61.1	104.3	105.1	93.0	51.2	95.3	116.2	116.2	51.2	89.5
GS47	Upper Namoi Alluvium	123.4	123.4	90.1	113.6	102.4	93.7	70.1	105.7	112.2	113.6	70.1	98.3
GS48	Upper Namoi Tributary Alluvium	1.77	1.77	0.55	0.38	0.21	0.23	0.18	0.28	0.19	0.55	0.18	0.29
GS24	Lower Gwydir Alluvium	33.0	33.0	29.3	46.4	43.3	35.5	23.8	35.5	37.5	46.4	23.8	35.9
GS43	Upper Gwydir Alluvium	0.72	0.72	0.07	0.07	0.07	0.07	0.12	0.07	0.07	0.12	0.07	0.08
GS8a	Goulburn-Murray: Shepparton Irrigation Region	244.1	244.1	41.3	35.5	43.7	79.5	54.2	43.4	96.3	96.3	35.5	56.3
GS8c	Goulburn-Murray: Sedimentary Plain	203.5	223.0	101.2	98.4	136.5	141.5	138.9	120.9	149.1	149.1	98.4	126.6

* Included for consistency to complement calculations done in section 3 of this report

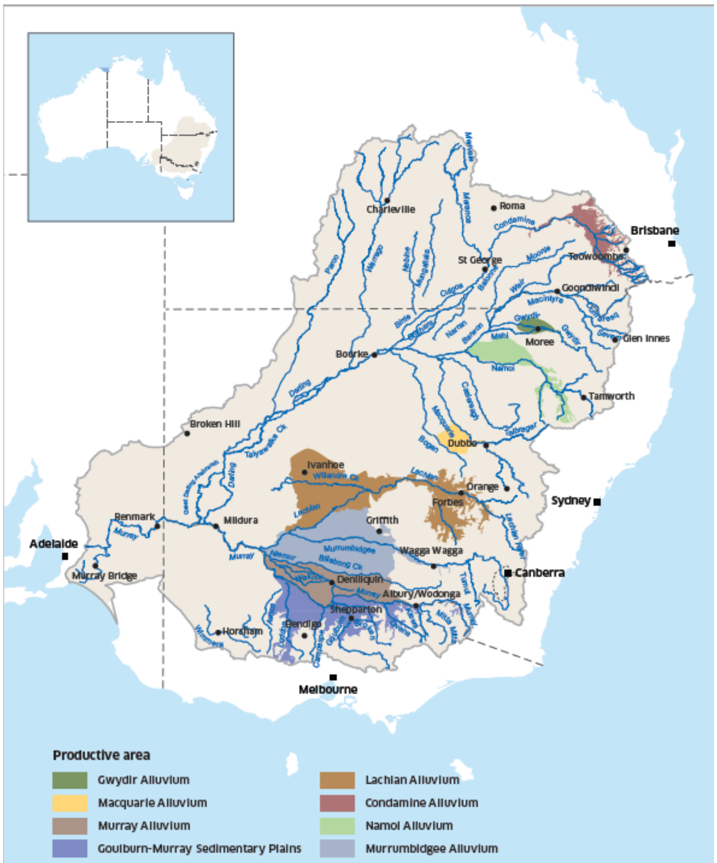

Figure 3 Main alluvial systems in the Murray-Darling Basin (from https://www.mdba.gov.au/publications/products/groundwater-alluvial-areas-map, accessed 12/11/2021)

These 8 alluvial systems concentrate on average 75% of the total groundwater use across the MDB for the period 2012-13/2018-19, with more recent estimates bringing this value closer to 80% (Figure 4).

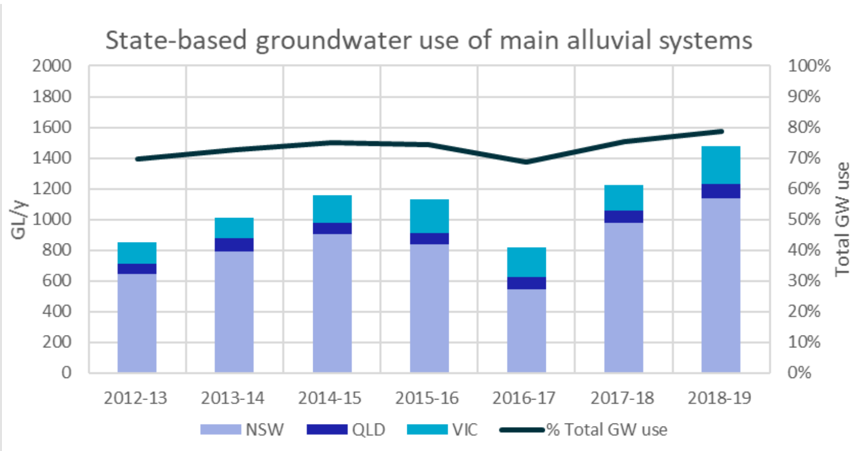

Figure 4 Groundwater use across states for the main alluvial aquifers listed and percentage of contribution to total groundwater use

At Basin state level, in New South Wales **Gwydir**, **Namoi**, **Macquarie**, **Lachlan**, **Murrumbidgee**, and **Murray** alluvial systems represent on average 80% of the groundwater use, with more recent estimates bringing this value to 84%. Most of the remaining groundwater use is concentrated in 5 SDL resource units (Kanmantoo Fold Belt MDB – GS19, Gunnedah-Oxley Basin MDB – GS17, New England Fold Belt MDB – GS37, Western Porous Rock – GS50, and Lachlan Fold Belt MDB – GS20) ranging on average between 8.2 GL/y and 81 GL/y for the period 2012-13 to 2018-19. In Queensland, **Condamine** alluvial system accounts on average for 43% of the groundwater use, with other 3 SDL resources units accounting for a remaining 49% of the groundwater use (Upper Condamine Basalts – GS65, Queensland Border Rivers Alluvium – GS54, and St. George Alluvium: Condamine–Balonne (deep) – GS61b) ranging between 11.3 GL/y and 67.3 GL/y. In Victoria, the **Goulburn-Murray** alluvial system accounts on average for 88% of the total groundwater use, with the SDL GS8b (Goulburn-Murray: Highlands) bringing this figure to 95% by adding an average consumption of 14.2 GL/y for the period 2012-13 to 2018-19.

2 Groundwater level trend analysis in major alluvial aquifers of the Murray-Darling Basin

This section is based on a published research article: ***Fu, G., Rojas, R., Gonzalez, D. (2022) Trends of groundwater levels in alluvial aquifers of the Murray-Darling Basin and their attributions. Water, 14, 1808, https://doi.org/10.3390/w14111808***. The following sections contain a summary of the main methods and results published in this article.

2.1 Scope of the trend analysis

Groundwater in the MDB is a valuable and limited resource. The most common method to assess the groundwater resource is to analyse groundwater levels, which are measured at specific (and limited) bore locations through time. Trends in groundwater levels are an integrative response to multiple forcing functions over different spatial and temporal scales (Tillman & Leake, 2010). Groundwater level trends can therefore be used to explain groundwater processes such as recharge and discharge/extraction cycles, as a direct reflection of rising or falling groundwater levels (or depth-to-water table, DTW) through time.

Literature about trend analysis in groundwater levels is abundant with methods such as Mann-Kendall/Sen's Slope estimator (Fang et al., 2019; Lasagna et al., 2020; Schmid et al., 2017), hydrograph analysis (Zeru et al., 2020) and regression analysis (Fu et al., 2019; Tillman & Leake, 2010; Zeru et al., 2020) dominating the literature. Alternative techniques such as innovative trend analysis (ITA) have been recently proposed (Dong et al., 2020).

The Bureau of Meteorology has recently deployed a digital product termed "Australian Groundwater Insight", which presents groundwater levels trend analysis of recovery peaks for 5-, 10- and 20-year periods for upper, middle and lower aquifers across Australia. The methods report for the trend analysis describes 3 methodologies to detect trends in groundwater levels (Sharples et al., 2021), with the linear trend method being used in the Australian Groundwater Insight.

We aim at providing a methodologically consistent and basin-scale trend analysis of groundwater levels in the main alluvial aquifers of the MDB using a consistent 40-year time window contained between years 1971-2021. The trend analysis performed is based on robust and widely applied statistical techniques and is performed on 910 observation bores, out of nearly 1200 available bores for monitoring in the MDB. Observation bores contain at least 2 records per year in order to calculate the mean, minimum and maximum depth-to-water table (DTW) per bore. For spatial consistency, we performed the trend analysis for each of the Sustainable Diversion Limits (SDL) groundwater resource units within the main alluvial sequences in the MDB, i.e. at SDL-scale. The contribution of this work lies in presenting a temporally and spatially consistent trend analysis for the main alluvial aquifers of the MDB to obtain a regional perspective of the status of key groundwater resources in the Basin. At the same time, we attempt to disentangle regional trend patterns by attributing potential drivers to these regionalized trends in groundwater levels.

2.2 Methods for groundwater level trend analysis

2.2.1 Kendall test and Sen's slope

The non-parametric Kendall's test (Kendall, 1975; Hirsch et al., 1982) can be used to detect the significance of the trends. A hypothesis test is based on the normalized Kendall's statistic *Z*:

$$Z = \begin{cases} \frac{S-1}{(\mathrm{Var}(S))^{1/2}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{(\mathrm{Var}(S))^{1/2}} & \text{if } S < 0 \end{cases} \qquad [1]$$

where,

$$Var(S) = \{\mathrm{n}(\mathrm{n}-1)(2\mathrm{n}+5) - \textstyle\sum_t t(t-1)(2t+5)\}/18 \qquad [2]$$

$$S = \textstyle\sum_{k=1}^{n-1}\sum_{j=k+1}^{n} \mathrm{sgn}\left(x_j - x_k\right) \qquad [3]$$

$$\mathrm{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases} \qquad [4]$$

The null hypothesis, H_o, meaning that *Z* is not statistically significant, i.e., no statistically significant increasing/decreasing trend of groundwater level, is accepted if $-Z_{\alpha/2} < Z < Z_{\alpha/2}$, where $Z_{\alpha/2}$ are the standard normal deviates. Correspondingly, it is accepted that H_1 or *Z* are statistically significant if $Z < -Z_{\alpha/2}$ or if $Z > Z_{\alpha/2}$ (Fu et al., 2004). As it is possible that some bores have an increasing trend and others decreasing, the two-sided hypothesis was chosen (Fu et al., 2004). The same significance level α=0.05 as in the linear trend analysis was used to detect whether a trend was statistically significant.

In addition to identifying whether a trend exists, it is also important to establish the magnitude of the trend. The trend magnitude β, an estimator developed by Hirsch et al. (1982) based on that proposed by Sen (1968), is defined as:

$$\beta = \mathrm{median}\ \frac{X_j - X_i}{j-i} \qquad [5]$$

where $1 < i < j < \mathrm{n}$. The slope estimator is the median over all possible slope combinations of pairs for the whole dataset. For a dataset of n years, the number of all possible combination will be $n(n-1)/2$.

2.2.2 Linear trend

This is a simple and commonly used statistical method to detect a linear trend of a time series of a variable of interest, such as rainfall, temperature, or groundwater level. The method basically builds a linear regression model between the variable of interest vs time, which considers all data points equally and minimizes the sum of the square of the distance of each point from the line. The trend magnitude is the slope of this line (*a*) and its statistical significance can be tested by hypothesis testing of this slope being equal to zero. The statistical significance of this linear slope, i.e., whether $a = 0$, is tested by a t statistic,

$$t = \frac{\hat{a}}{s_e/\sqrt{s_x}} \qquad [6]$$

which has a t distribution with $n\text{-}2$ degrees of freedom, meaning a p-value can be obtained from this statistic, and n is the sample size. The parameters s_e and s_x are computed as:

$$s_e^2 = \frac{1}{n-1}\sum_{i=1}^{n} e_i^2 \qquad [7]$$

$$s_x = \sum_{i=1}^{n}(t_i - \bar{t})^2 \qquad [8]$$

where e are the residuals of the regression as $e = (\hat{a} * t + \hat{b}) - y$. The significance level α=0.05 (which corresponds to a p-value < 0.025 with a two-sided test) is used in this study to detect whether a linear slope is statistically significant.

2.2.3 Two-period comparison and Innovative Trend Analysis (ITA)

The two-period method compares mean groundwater levels between 2 periods of time that do not necessarily need to have equal lengths. To further explore the trends at different quantiles by using the innovative trend analysis (ITA)(Dong et al., 2020; Şen, 2012), equal lengths of periods are required. If the mean value of the second half period of the groundwater level is higher than that of the first half, a rising trend is detected, and vice versa. The statistical significance can be tested to determine whether the values are substantially different:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\frac{\sqrt{s_1^2 + s_2^2}}{\sqrt{n}}} \qquad [9]$$

where $\overline{x_1}$ and $\overline{x_2}$ are mean values of first and second half respectively. The s_1 and s_2 are standard deviations of 2 periods. The statistic t has a t-distribution with $n\text{-}1$ degrees of freedom. The trend magnitude, S-slope, is estimated based on the ITA method (Dong et al., 2020; Şen, 2012):

$$S = \frac{2 * (\overline{x_2} - \overline{x_1})}{n} \qquad [10]$$

The advantage of extending a simple two-period method into the ITA method is that it can show different trend directions and magnitudes for different quantiles of groundwater levels. For example, it can show where trends for lower values differ in both direction and magnitude from trends at higher values. This can provide insights into the likely mechanisms driving observed trends.

2.3 Results of trend analysis on groundwater levels

The above 3 trend analysis methods were used in this work to detect long-term trends of annual mean/minimum/maximum depth-to-water table (DTW) at 910 bores. The results showed:

1. There is clearly an overall increasing trend of DTW for the MDB alluvial aquifers during the last 50 years (1971–2021), regardless of groundwater level statistics (mean, minimum and maximum annual values) and trend detection methods used in the analysis (non-parametric Kendall test, linear regression, and two-period comparison) (Table 2). About 90–95% of groundwater bores showed an increasing trend in depths, of which 84–87% were statistically significant at a $\alpha=0.05$ level. In contrast, only 7–9% groundwater bores showed a decreasing trend in depths of which only 4–5% were statistically significant (Table 2).

Table 2 Numbers of bores with decreasing and increasing trends in DTW and statistical significance level in 8 alluvial systems of the MDB

Methods	Variables	Sig Decrease	Decrease	Increase	Sig Increase
Kendall test	Mean DTW	39	27	55	789
	Min DTW	37	32	49	792
	Max DTW	40	36	64	770
Linear trend	Mean DTW	41	22	49	798
	Min DTW	42	28	43	797
	Max DTW	44	30	62	774
Two-period comparison	Mean DTW	41	28	55	786
	Min DTW	36	37	51	786
	Max DTW	42	36	74	758

2. The 3 methods employed showed similar statistical significances and magnitudes, but differences exist (Table 3). A general conclusion would be that all 3 methods should be used for trend analysis, and their consistent results could enhance our confidence and their differences should be further investigated to uncover potential unforeseen hydrological processes acting at different temporal and/or spatial scales.

Table 3 Numbers of bores with consistent trend significance for annual mean depth-to-water table (DWT) among 3 methods applied to 910 bores in 8 alluvial aquifers of the MDB

Methods		Linear trend				Two-period			
		SigDe*	Decrease	Increase	SigIn*	SigDe	Decrease	Increase	SigIn
Kendall	SigDe	**36**	3	0	0	**36**	3	0	0
	Decrease	5	**17**	5	0	4	**18**	5	0
	Increase	0	1	**39**	15	1	6	**34**	14
	SigIn	0	1	5	**783**	0	1	16	**772**
Linear trend	SigDe					**37**	4	0	0
	Decrease					3	**15**	3	1
	Increase					1	8	**37**	3
	SigIn					0	1	15	782

*SigDe: Statistically significant decreasing trend at α=0.05 level; Decrease: Statistically insignificant decreasing trend at α=0.05 level; Increase: Statistically insignificant increasing trend at α=0.05 level; and SigIn: Statistically significant increasing trend at α=0.05 level.

3. In terms of trend magnitudes, these ranged from -0.25 to about +1.00 m/year across the 3 annual DTW statistics (mean, minimum and maximum annual values) and the 3 techniques used during the 50-year period assessed (1971–2021). The median and mean values among 910 groundwater bores were 0.09 and 0.11–0.13 m/year, respectively (Table 4).

   While the maximum trend magnitude can be as high as +1.0 m/year, the 95th percentile is about 0.3–0.4 m/year (Table 4). The 5–10% negative trend magnitudes were consistent with trend significance results (Table 4).

Table 4 Statistics of groundwater level trend magnitudes in 8 alluvial systems of the MDB (m/year)

Methods	Variables	Min	P5	P10	P25	Med	Mean	P75	P90	P95	Max
β	Mean DTW	-0.22	-0.01	0.01	0.04	0.09	0.13	0.20	0.30	0.35	1.01
	Min DTW	-0.22	-0.01	0.01	0.04	0.09	0.12	0.18	0.26	0.29	0.99
	Max DTW	-0.22	-0.01	0.00	0.04	0.09	0.14	0.21	0.33	0.43	1.01
Linear trend	Mean DTW	-0.23	-0.01	0.01	0.05	0.09	0.13	0.20	0.30	0.37	0.99
	Min DTW	-0.25	-0.01	0.01	0.05	0.09	0.12	0.19	0.26	0.30	0.98
	Max DTW	-0.22	-0.01	0.01	0.04	0.09	0.14	0.22	0.33	0.43	1.01
Two-period (*S*-slope)	Mean DTW	-0.22	-0.01	0.01	0.04	0.09	0.12	0.20	0.28	0.33	0.83
	Min DTW	-0.25	-0.01	0.01	0.04	0.09	0.11	0.18	0.25	0.29	0.82
	Max DTW	-0.20	-0.01	0.01	0.04	0.09	0.13	0.20	0.31	0.40	0.83

The cumulative distribution function (cdf) of the trend magnitude for the annual mean DTW from the Beta magnitude (β) (Figure 5) shows the detailed distribution of trend magnitudes. Other statistics (min and max DTW) and methods showed a similar distribution as the one presented in Figure 5.

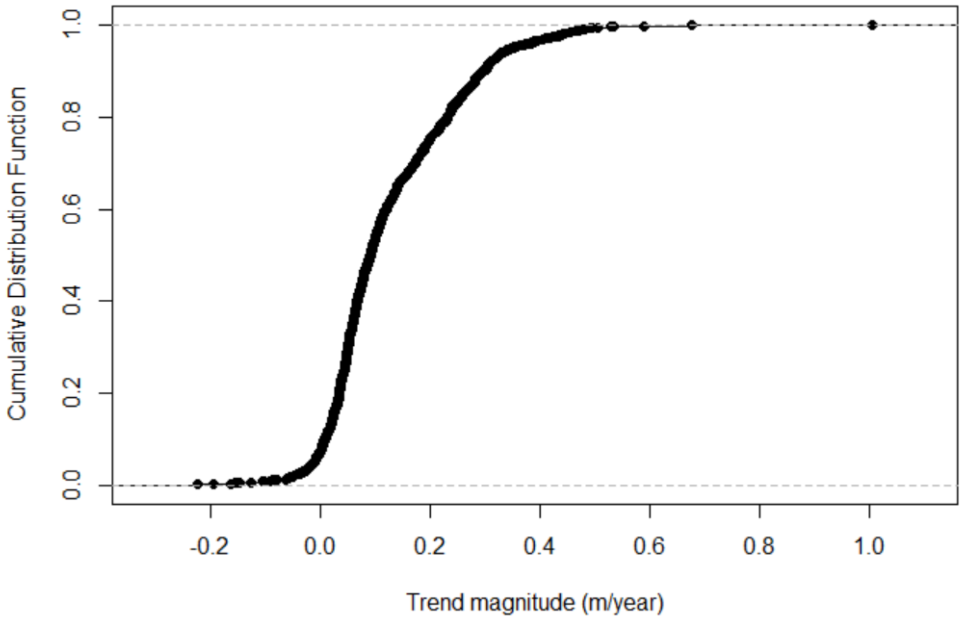

Figure 5 Cumulative distribution function of annual mean DTW trend magnitudes (Beta method)

4. Figure 6 shows the spatial distributions of trend significance and magnitudes for annual mean DTW using the Kendall test. The overall statistically significant increasing DTW trend was clearly observed across all areas.

   Most groundwater bores with declining groundwater level trends (i.e., increasing DTW) showed a magnitude of 0.0–0.2 or 0.2–0.3 m/year. There were far fewer bores with decreasing DTW (increasing water levels) (Figure 6c and 6e, respectively). While trends were statistically significant, magnitudes for these bores were generally in the lower -0.2–0 m/year range (Figure 6d and 6f, respectively).

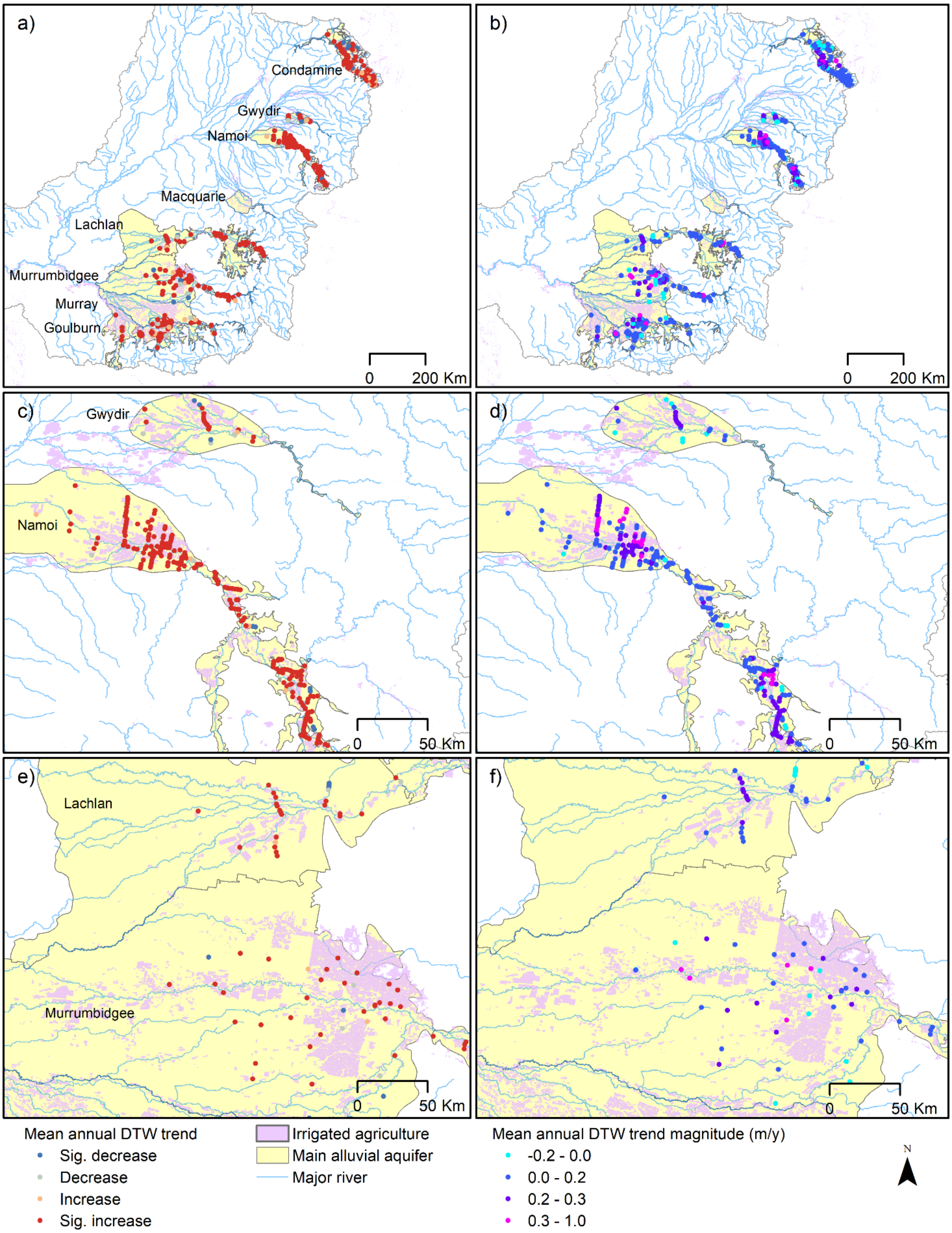

Figure 6 Spatial distribution of DTW trend significance (Kendall test, α=0.05) and magnitude at MDB scale (a, b) and finer scale examples (c, d, e, f).

5. The annual minimum DTW showed a smaller trend magnitude than annual mean DTW, and the annual maximum DTW showed a larger trend magnitude than mean DTW.

6. Innovative trend analysis (ITA), which is less popular than the Kendall test and linear trend, could also be used to explore the attributions to groundwater level trends observed by exploring differences trend for different quantiles.

7. Table 5 shows the resulting trend magnitudes for the mean annual DTW recorded in the SDLs analysed. Only 14 SDLs fulfilled the data filtering process (40 years with at least 2 records per year per bore) to proceed with the trend analysis. Results showed that mean trend magnitudes vary between 0.03 m/y and 0.19 m/y, with an average across SDLs equal to 0.11 m/y. SDLs showing above average increasing trends for mean annual DTW were identified as: Lower Gwydir Alluvium (GS24), Lower Murrumbidgee Deep Alluvium (GS28b), Lower Namoi Alluvium (GS29), Mid-Murrumbidgee Alluvium (GS31), Upper Namoi Alluvium (GS47), Upper Condamine Alluvium-CCA (GS64a) and Goulburn-Murray: Sedimentary Plain (GS8c). Similarly, the previous group of SDLs and Upper Condamine Alluvium (Tributaries) (GS64b) showed maximum trend magnitudes above average across all SDLs analysed.

Table 5 Statistics of depth-to-water table (DTW) trend magnitudes (m/y) per SDLs. Beta value for mean annual DTW

SDL Resource Units	n	Min	Median	Mean	Max	Average GW use 2012/2019 (GL/y)	Maximum GW use 2012/2019 (GL/y)
Upper Condamine Alluvium (Tributaries) (GS64b)	73	-0.19	0.04	0.06	1.01	33.2	35.6
Upper Condamine Alluvium (CCA) (GS64a)	74	-0.10	0.10	0.12	0.48	46.7	57.7
Lower Gwydir Alluvium (GS24)	48	-0.13	0.10	0.12	0.35	35.9	46.4
Upper Namoi Alluvium (GS47)	174	-0.10	0.14	0.16	0.53	98.3	113.6
Lower Namoi Alluvium (GS29)	155	-0.06	0.17	0.19	0.68	89.5	116.2
Lower Lachlan Alluvium (GS25)	31	-0.03	0.06	0.10	0.33	108.6	131.8
Upper Lachlan Alluvium (GS44)	56	0.01	0.09	0.11	0.42	57.4	89.4
Mid-Murrumbidgee Alluvium (GS31)	90	0.00	0.08	0.12	0.35	39.0	55.6
Lower Murrumbidgee Shallow Alluvium (GS28a)	12	-0.06	0.04	0.03	0.09	6.9	8.3
Lower Murrumbidgee Deep Alluvium (GS28b)	36	-0.22	0.17	0.18	0.50	261.6	377.9
Upper Murray Alluvium (GS46)	6	-0.02	0.03	0.05	0.16	12.1	17.8
Lower Murray Deep Alluvium (GS27b)	4	-0.01	0.04	0.11	0.36	68.7	110.7
Goulburn-Murray: Sedimentary Plain (GS8c)	55	0.01	0.09	0.15	0.59	126.6	149.1
Goulburn-Murray: Shepparton Irrigation Region (GS8a)	96	-0.15	0.04	0.04	0.21	56.3	96.3

8. For the period with reported metered groundwater use data (2012-2019), a moderate positive correlation (r=0.68, p-value=0.008) between groundwater use and increasing trends in mean DTW at SDL scale was detected, thus suggesting attribution of groundwater use contributing to deepening of DTW in the alluvial aquifers (Table 5). Complexity of groundwater dynamics at local scale however hinders the attribution process from bore to bore, or even for specific hotspots within alluvial aquifers.

9. The overall increasing trend in DTW across all alluvial aquifers can be attributable to changes in recharge from rainfall and groundwater extraction, and irrigation seems responsible for some decreasing trends in DTW, i.e., an increase in groundwater level most likely due to localized recharge processes in the shallow aquifers derived from irrigation.

3 Prioritisation of alluvial aquifers of the Murray-Darling Basin

Groundwater systems are prioritised according to different criteria, including the role of aquifers in sustaining groundwater-dependent ecosystems (GDEs), vulnerability to changes in recharge patterns, long-term sustainability of available groundwater resources, groundwater quality aspects, among others. Currie et al. (2010) and Barron et al. (2011) proposed a method to prioritise large-scale aquifers based on the concepts of "aquifer importance" and "aquifer sensitivity". In addition, Gleeson et al. (2012) proposed the groundwater footprint as a metric to quantify groundwater stress from a quantity perspective. Kourgialas et al. (2018) further expanded this metric to account for water quality aspects when quantifying the groundwater footprint.

The next sections briefly summarise the definition of these metrics and the results when applying them to the main alluvial aquifers of the MDB. This section is based on an article (in preparation) to be submitted for publication to Journal of Hydrology: Regional Studies.

3.1 Aquifer prioritisation methodology

3.1.1 Aquifer importance index

Aquifer importance is defined as the *"significance of the groundwater resource for consumptive use and for the environment"* and is calculated following Currie et al. (2010) and Barron et al. (2011). It combines in a single index the current levels of groundwater extraction, the volume of the groundwater resource, and the occurrence of groundwater-dependent ecosystems (GDEs). Following Barron et al. (2011) the aquifer importance index can be calculated as follows:

$$I = \frac{E}{E_{MAX}} * \frac{SY}{SY_{MAX}} * f(Baseflow\ GDEs) * f(other\ GDE\ types) \qquad [1]$$

where I is aquifer importance; E is current level of extraction (ML/y); E_{MAX} is the maximum level of extraction recorded for the aquifers being analysed in the dataset (ML/y); SY is sustainable yield (ML/y); SY_{MAX} is maximum sustainable yield for the aquifers being analysed in the dataset (ML/y). *f(baseflow GDEs)* represents a weighting factor accounting for the presence of river baseflow GDEs; and *f(other GDEs)* represents a weighting factor representing other GDE types. Both GDE functions are numerically defined simply by the presence or absence of GDEs and calculated as follows:

$$f(GDEs) = \begin{cases} 0.85 & where\ GDEs\ are\ identified\ in\ the\ groundwater\ source \\ 0.15 & where\ no\ GDEs\ are\ identified\ in\ the\ groundwater\ source \end{cases} \qquad [2]$$

Accounting more accurately for the occurrence of GDEs in the alluvial aquifers of the MDB however might require considering other features such as species diversity, areal extent, and confidence degree in the GDE classification.

A revised version of equation [1] was proposed and used in this report and was defined as:

$$I_i = \frac{Actual\ GW\ take_i}{Max(Actual\ GW\ take_i\colon i=1,\dots,n)} * \frac{SDL_i}{Max(SDL_i\colon i=1,\dots,n)} * f(GDE_i) \qquad [3]$$

where *i* is the indicator of groundwater SDL resource unit analysed, *n* is the total number of SDL resource units, *Actual GW take*$_i$ (ML/y) represents metered groundwater use reported in the transition Period Water Take Reports (2012-2019) for the groundwater SDL resource unit *i*, and SDL_i represents the groundwater sustainable diversion limit (ML/y) associated with SDL resource unit *i*. The max operator represents the maximum value in the set of SDL resource units analysed. $f(GDE_i)$ represents the factor accounting for GDE diversity in the corresponding *i*-th SDL groundwater resource unit.

In equation [3] we have aggregated the occurrence of GDEs in specific SDL units in a single factor, and have improved on the definition of this metric to address the issues mentioned above by using the latest available spatial data in the GDE Atlas published by the Bureau of Meteorology (BoM) (http://www.bom.gov.au/water/groundwater/gde/) (see Section 3.5). From the GDE Atlas it is possible to obtain additional spatial information on aquatic ecosystems relying on the surface expression of groundwater, which also includes surface water ecosystems which may have a groundwater component, such as rivers, wetlands and springs. Spatial features of this dataset such as GDE potential, GDE ecotypes, eco-hydrogeological zone, and specific areal extents, can help further refine the $f(GDE_i)$ diversity metric to obtain a more robust and representative importance index. The GDE Atlas defines 3 main classes of GDEs: aquatic, terrestrial and subterranean. Within the study extent no subterranean features are present. This study used grouped aquatic GDEs based on ecotype (wetland, river, spring) and eco-hydrogeological zone resulting in 26 classes for aquatic GDEs. Terrestrial GDEs (one vegetation ecotype class) were grouped according to sub-ecotype resulting in 476 classes.

To improve on accounting for the presence of GDEs in calculating the importance index for each SDL resource unit, we adapted 2 widely used diversity indices, i.e. Shannon and Simpson Diversity Indices (Gorelick, 2006; Spellerberg & Fedor, 2003) to use class areas instead of species counts within SDLs as defined in the following equations:

$$Shannon\ Diversity\ Index = H = \sum_{i=1}^{n} p_i \ln{(p_i)} \qquad [4]$$

where p_i is proportional area of individual classes in the *i*-th classes, *ln* is natural logarithm, and *n* is the area of each class in the corresponding SDL resource unit.

$$Simpson\ Diversity\ Index = D = 1 - \left(\sum n(n-1)\right)/N(N-1) \qquad [5]$$

where n is area of each class, and N is the total area of all classes in the corresponding SDL resource unit.

These indices were also calculated on filtered GDE data to exclude areas defined as ‘low’ or ‘unknown’ GDE potential in the GDE Atlas.

Finally, we explored the impact on the quantification of the importance index by weighting the diversity indices by the ratio between GDE area and total SDL resource unit area ($Area_{GDE}/Area_{SDL}$). This was done to account for the spatial extent of GDEs in the corresponding SDL resource units and was calculated for filtered (by GDE potential as defined in the GDE Atlas) and unfiltered data.

3.1.2 Aquifer sensitivity index

The sensitivity index combines the size of the aquifer resource, current level of groundwater use, and the aquifer’s capacity to buffer potential changes in recharge rates. Following Barron et al. (2011) the aquifer sensitivity index is calculated as follows:

$$Se = \frac{E}{SY} * f(R{:}S) \qquad [6]$$

where E is current level of groundwater use (ML/y); SY is sustainable yield (ML/y); and $f(R{:}S)$ is a function describing the ratio between aquifer recharge (R) and aquifer storage (S), which is termed the ‘responsiveness metric’. This responsiveness metric relates to the buffering capacity of individual aquifers to ‘absorb’ potential changes in recharge rates. A high recharge-to-storage ratio will indicate a higher degree of sensitivity as there will be minimal buffering capacity (storage) to absorb changes in recharge (Barron et al., 2011; Currie et al., 2010). Given the uncertainties in recharge and storage estimations (Barron et al., 2011), $f(R{:}S)$ is expressed similar to a membership function, which defines the following ranking for weighting the relevance of the responsiveness metric:

$$f(R{:}S) = \begin{cases} 0.9 & high\ R{:}S \\ 0.3 & moderate\ R{:}S \\ 0.01 & low\ R{:}S \end{cases} \qquad [7]$$

A revised version of equation [6] was proposed and defined as:

$$Se_i = \frac{Actual\ GW\ take_i}{SDL_i} * f(R{:}S)_i \qquad [8]$$

where $i=1,..,n$ is the indicator of the groundwater SDL resource unit analysed, n is equal to the number of SDL resource units in the dataset, $Actual\ GW\ take_i$ (ML/y) represents metered groundwater use reported in the transition Period Water Take Reports (2012-2019) for the groundwater SDL resource unit *i*, SDL_i represents the groundwater sustainable diversion limit (ML/y) associated with SDL resource unit *i*, and $f(R:S)_i$ represents the responsiveness metric factor for the *i*-th groundwater SDL resource unit.

In order to define the 3 categories (high, moderate and low R:S ratios), we employed recharge estimates reported in the groundwater report cards (MDBA, 2020a) and groundwater resources description reports used as supporting documents for Water Sharing Plans in NSW (NSW-DPIE, 2019b; NSW DPI, 2018c, 2018b, 2018a, 2019a, 2019b). Similarly, we employed average values of standing water levels, base level of the aquifer, planar areas, aquifer types, estimates of porosity as reported in the groundwater resource description reports for SDLs in New South Wales. We used a similar approach for groundwater SDL resource units located in Queensland and Victoria using referenced data for alluvial aquifers (DNRME, 2018; McNeil et al., 2018; MDBA, 2020a; OGIA, 2016; Water, 2015; Welsh, Herron, Rohead-O'Brien, Cook, et al., 2014) or the depth of regolith digital product (Wilford et al., 2018) when alluvial depth data was not available.

3.1.3 Aquifer priority index

Importance and sensitivity indices can be combined following the standardisation process described in Barron et al. (2011) and detailed in Appendix A.1. The aquifer prioritisation is obtained by the multiplication of both metrics:

$$Aquifer\ Prioritization = \frac{I}{I_{max}} * Se_{standardized} \qquad [9]$$

Barron et al. (2011) and Currie et al. (2010) proposed a revised method to prioritise aquifers systems based on an ordination approach, where aquifers deemed as important and sensitive are regarded as priority. Under this revised approach, the following categories can be obtained:

- Important aquifer systems (low sensitivity rating)
- Sensitive aquifer systems (low importance rating)
- Priority aquifer systems (high importance and high sensitivity rating)

3.2 Groundwater footprint methodology

Gleeson et al. (2012) proposed the groundwater footprint (GF) as a metric to assess the large-scale water balance between aquifer inflows and outflows. The GF expresses the area required to sustain groundwater use and GDE services of a given region of interest, and is defined as:

$$GF = A\left[\frac{C}{(R-E)}\right] \qquad [10]$$

where *A* is the areal extent of the region of interest (e.g. aquifer area or management area) (L^2), C is the area-averaged annual groundwater abstraction, *R* is the area-averaged annual recharge rate, and *E* is the groundwater contribution to environmental streamflow. All these expressed in consistent units. In this analysis, recharge rates reported for each SDL (see section 3.3.2) as well as the metered groundwater use for each groundwater SDL analysed (see Table 1) were obtained from reported data (see references in section 3.3.2).

Gleeson et al. (2012) and Mahdavi (2021) suggest alternative ways to approach the groundwater contribution to streamflow (*E*) to calculate the groundwater footprint, such as hydro-ecological studies, direct measurements of springs, hydrological modelling results, expert judgement, expressed as a fraction of recharge, or as a low-flow statistic as defined by Smakhtin et al. (2004). The groundwater contribution to streamflow (*E*) was obtained from modelling results reported in the groundwater report cards (MDBA, 2020a), and groundwater resource description reports for the Murrumbidgee alluvium resource (NSW-DPIE, 2019b) and Border Rivers alluvium resource (NSW-DPIE, 2019a; Welsh, Herron, Rohead-O'Brien, Ransley, et al., 2014). For the SDLs representing Upper Lachlan (GS44), Upper Gwydir (GS24), Goulburn-Murray: Shepparton Irrigation Region (GS8a) and Goulburn-Murray: Sedimentary Plain (GS8c), the groundwater contribution to streamflow (*E*) was obtained by estimating the Q_{95} from representative gauging stations located along river reaches in these alluvial systems. For the SDLs located in Victoria we used the spatial dataset describing the groundwater-surface interactions to identify gaining river sections where contributions from groundwater are to be expected (VIC-DELWP, 2020).

Equation [10] however only accounts for groundwater quantity thus neglecting the groundwater quality aspects that might potentially impact groundwater use. Recently, Kourgialas et al. (2018) proposed a revised version of the groundwater footprint accounting for groundwater quality aspects, which is defined as:

$$iGF = GF \times \left(1 + n\left[CF_1\frac{A_1}{A} + CF_2\frac{A_2}{A} + \cdots + CF_n\frac{A_n}{A}\right]\right) \qquad [11]$$

where, *GF* is the groundwater footprint as defined in equation 10, *n* is the number of contaminants in the aquifer system, $CF_{(1..n)}$ is a factor for contaminant (*j*), with *j*=1,…,*n*, with CF_j equal to 1 if contaminant is present or above a threshold, and zero otherwise, $A_{(1..n)}$ is the extent of the contaminated area, and *A* is the areal extent of the region of interest. Based on this equation, the larger the area of contamination and the number of contaminants present, the larger the iGF footprint.

The ratio of both GF and iGF by the aquifer area (A) is interpreted as a groundwater stress metric, with GF/A >1 and iGF/A > 1 indicating unsustainable consumption of groundwater resources and evidence of contamination in a particular aquifer system (Kourgialas et al., 2018).

3.2.1 Groundwater salinity analysis methods for calculating the iGF

Groundwater salinity data were downloaded from the BoM NGIS and attributed to SDL resource units using the same method described for groundwater level data (see Section 2 or Fu et al. (2022)). Data were filtered using the quality flag attribute (0) to remove poor quality data. The upper and lower 2% of data were also removed to filter out extreme values (i.e. min of 1, max of 450,000 uS/cm). Bores with less than 2 salinity observations were removed. Percentiles were calculated for each bore and the 95th percentile values were used to interpolate across the SDL areas. Salinity data distributions were positively skewed for 20 of the 22 SDL resource units.

Geostatistical interpolations were tested to create prediction surfaces of salinity across SDL areas from bore data. Model performance was assessed using cross-validation and models that minimised error using root-mean-square (RMS) and mean standardised error (ME) as the main indicators of fit were selected.

Geostatistical analyses were performed for all SDL areas together except for the Goulburn-Murray: Shepparton Irrigation Region that overlies the Goulburn-Murray: Sedimentary Plain area. There were insufficient data points in the other shallow SDL areas (Lower Murray Shallow Alluvium, Lower Murrumbidgee Shallow Alluvium) to enable reliable spatial interpolation. Due to the high number of possible model/parameter combinations, separate model testing for each SDL area was not feasible.

Ordinary kriging was selected on the basis that the variety of scale dependent trends across a large study area, in this case multiple aquifers, would be impossible to model using universal kriging options. Semi-variogram models were used that compared untransformed and transformed data with stable, circular, spherical, K-Bessel, and exponential models. Parameters (nugget, partial sill, lag size) were optimised for range in each instance.

For all SDLs (except the Goulburn-Murray: Shepparton Irrigation Region), the best fit (RMS 4463, ME -0.0027) was obtained using: Box-Cox transformation, circular semi-variogram model, 4 sector 45° offset standard neighbourhood with a minimum of 2 and maximum of 5 neighbours.

For the Goulburn-Murray: Shepparton Irrigation Region SDL area, the best fit (RMS 4893, ME -0.0014) was obtained using: Box-Cox transformation, K-Bessel semi-variogram model, 8 sector standard neighbourhood with a minimum of 2 and maximum of 5 neighbours.

Following the creation of prediction surfaces, continuous values were contoured into salinity classes TDS (mg/L) following the Recharge Risk Assessment Method (RRAM) described in MDBA (2020a). These classes are shown in Table 2.

Table 6 Salinity classes described in the RRAM (MDBA, 2020a) **and used to interpolate salinity values to estimate *iGF***

Salinity Class	Salinity (mg/L)
Class 1	0-1,500
Class 2	1,500-3,000
Class 3	3,000-14,000
Class 4	>14,000

Total areas of these salinity classes within each SDL were calculated and used as the inputs to calculate the iGF using equation [11] for each salinity class.

3.3 Results of prioritisation of alluvial aquifers in the MDB

3.3.1 Accounting for GDE diversity in the importance index

As defined in section 3.1.1, we used GDE class areas instead of species counts within SDLs for calculating the term accounting for GDEs in the importance index, *f(GDE)*. Table 7 summarises the main values employed to assess GDE diversity in the importance index. In the case of deep alluvial aquifers, GDEs are accounted for in the corresponding shallow alluvial aquifers (e.g. Lower Murrumbidgee Shallow and Lower Murray Shallow). To avoid double accounting but at the same time recognising the potential contributions to sustain GDEs by deep alluvial aquifers, deep alluvial aquifers were allocated a fraction of the maximum diversity indices calculated across all alluvial aquifers. This fraction is based on Barron et al. (2011) and Currie et al. (2010) who reported a value of 0.0225 when describing no presence of GDEs and a maximum value of 0.7225 when describing the presence of both terrestrial and aquatic GDEs. The resulting fraction from these values is 1/32. This fraction value has been applied to the maximum diversity index obtained across all SDLs and assigned to the Lower Murrumbidgee Deep Alluvium (GS28b) and Lower Murray Deep Alluvium (GS27b) in Table 7.

Table 7 GDE areas as reported from the GDE Atlas and GDE diversity indices (unweighted and weighted by proportional areas)

SDL id	SDL resource unit name	Total area GDEs (km²)	Percentage SDL area of all GDEs	Simpson Diversity Index (D)	Simpson Index weighted by proportional GDE area (DA)	Shannon Diversity Index (H)	Shannon Index weighted by proportional GDE area (HA)	Total area GDEs (km²) (*)	Percentage SDL area of all GDEs (*)	Simson Diversity Index (Df) (*)	Simpson Index weighted by proportional GDE area (DAf) (*)	Shannon Diversity Index (Hf) (*)	Shannon Index weighted by proportional GDE area (HAf) (*)
GS24	Lower Gwydir Alluvium	1021.97	35.36	0.8607	0.3043	2.2772	0.8051	545.14	18.86	0.6770	0.1277	1.4436	0.2723
GS25	Lower Lachlan Alluvium	6691.69	21.43	0.8226	0.1763	2.3795	0.5099	934.60	2.99	0.7486	0.0224	1.6115	0.0482
GS26	Lower Macquarie Alluvium	544.39	11.13	0.8843	0.0984	2.4772	0.2757	91.82	1.88	0.7670	0.0144	1.7866	0.0335
GS27a	Lower Murray Shallow Alluvium	9046.91	41.15	0.8342	0.3432	2.3453	0.9650	5192.17	23.61	0.7477	0.1766	1.8080	0.4269
GS27b	Lower Murray Deep Alluvium**	9046.91	41.15	0.0289	0.0156	0.0313	0.0313	5192.17	23.61	0.0288	0.0066	0.0313	0.0313
GS28a	Lower Murrumbidgee Shallow Alluvium	13396.20	33.44	0.9079	0.3036	2.8161	0.9417	2283.78	5.70	0.8985	0.0512	2.5244	0.1439
GS28b	Lower Murrumbidgee Deep Alluvium **	13396.20	33.44	0.0289	0.0156	0.0313	0.0313	2283.78	5.70	0.0288	0.0066	0.0313	0.0313
GS29	Lower Namoi Alluvium	1951.72	22.21	0.8545	0.1898	2.3341	0.5184	981.87	11.17	0.6598	0.0737	1.4644	0.1636
GS31	Mid-Murrumbidgee Alluvium	561.24	30.86	0.8254	0.2547	2.2610	0.6977	399.26	21.95	0.6995	0.1535	1.6491	0.3620
GS32	NSW Border Rivers Alluvium	130.23	28.81	0.8805	0.2537	2.7177	0.7830	71.47	15.81	0.8633	0.1365	2.4990	0.3952
GS33	NSW Border Rivers Tributary Alluvium	181.60	59.14	0.8445	0.4995	2.3412	1.3846	88.51	28.82	0.7373	0.2125	1.8583	0.5356
GS43	Upper Gwydir Alluvium	26.31	21.88	0.6980	0.1527	1.6905	0.3699	20.10	16.72	0.4999	0.0836	0.8974	0.1500
GS44	Upper Lachlan Alluvium	4197.49	26.22	0.8441	0.2213	2.5269	0.6625	2120.04	13.24	0.5794	0.0767	1.5975	0.2116
GS45	Upper Macquarie Alluvium	103.39	30.65	0.8716	0.2671	2.2906	0.7020	27.15	8.05	0.5859	0.0471	1.2481	0.1004
GS46	Upper Murray Alluvium	118.52	19.61	0.7487	0.1468	2.0410	0.4002	91.38	15.12	0.5954	0.0900	1.3950	0.2109
GS47	Upper Namoi Alluvium	917.16	20.78	0.8163	0.1697	2.1525	0.4474	211.46	4.79	0.8280	0.0397	2.0523	0.0983
GS48	Upper Namoi Tributary Alluvium	10.28	14.77	0.7820	0.1155	1.7493	0.2584	6.40	9.20	0.7170	0.0659	1.4514	0.1335
GS54	Queensland Border Rivers Alluvium	642.95	25.49	0.8228	0.2097	2.3434	0.5973	393.84	15.61	0.6516	0.1017	1.4987	0.2340
GS64a	Upper Condamine Alluvium (CCA)	286.05	5.33	0.7919	0.0422	1.9120	0.1019	130.12	2.42	0.3461	0.0084	0.8356	0.0203
GS64b	Upper Condamine Alluvium (Tributaries)	358.69	7.69	0.8162	0.0627	2.3298	0.1791	219.60	4.71	0.6090	0.0287	1.7175	0.0808
GS8a	Goulburn-Murray: SIR	847.70	10.43	0.9257	0.0966	3.1233	0.3258	821.94	10.11	0.9228	0.0933	3.1080	0.3144
GS8c	Goulburn-Murray: Sedimentary Plain	903.76	4.70	0.8918	0.0419	2.7098	0.1273	836.85	4.35	0.8865	0.0386	2.7095	0.1178

(*) GDE areas including only moderate to high potential GDEs as reported in the GDE Atlas (BoM), i.e., low and unknown GDE potential are filtered out
(**) These are defined as deep alluvial aquifers, *f(GDE)* is therefore defined following (Barron et al., 2011; Currie et al., 2010) as a fraction of the maximum value recorded across all alluvial aquifers analysed

Figure 7 shows the GDE area used for the calculation of the diversity indices and its corresponding percentage with respect to the total SDL resource unit area. It is interesting to note that for SDLs with large absolute values of total GDE area (Lower Lachlan Alluvium (GS25), Lower Murray Shallow Alluvium (GS27a), Lower Murrumbidgee Shallow Alluvium (GS28a), Upper Lachlan Alluvium (GS44)), these GDE areas represent between 21% and 41% of the total SDL area. If areas with low and unknown GDE potential are filtered out from the dataset, the GDE areas fluctuate between 3% and 24% of the total SDL area.

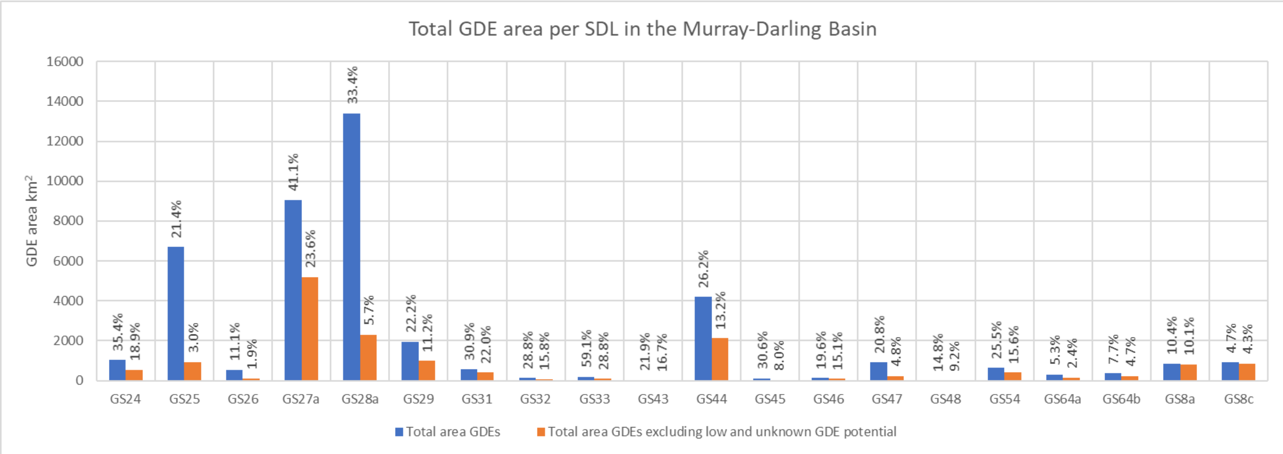

Figure 7 GDE area obtained from the GDE Atlas (BOM) for groundwater SDLs representing 8 main alluvial aquifers in the MDB. Percentages represent the ratio $Area_{GDE}/Area_{SDL}$

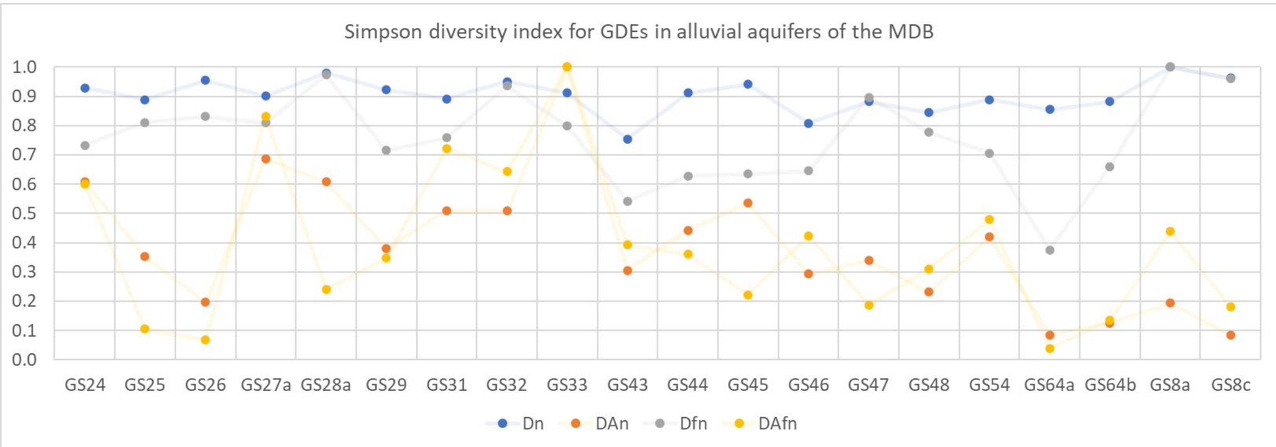

Figure 8 Normalised Simpson Diversity Index (Dn) weighted by $Area_{GDE}/Area_{SDL}$ (DAn) for alluvial aquifers in the MDB. Dfn and DAfn are the same metrics but using filtered out areas of low and unknown GDE potential

Figure 8 shows the normalised Simpson diversity index using all GDE areas (Dn) and areas of moderate and high potential GDEs for groundwater dependence (Dfn), and for 2 different weighting schemes, e.g., weighted by the proportional GDE area ($Area_{GDE}/Area_{SDL}$) (Dan); and weighted by the proportional area of moderate to high potential GDEs ($Area_{GDE\_f}/Area_{SDL}$), i.e., filtering out unknown and low potential GDE areas. In general, Figure 6 shows that diversity indices show less variability when calculated directly from the GDE Atlas data (Dn). The largest variability in diversity indices is obtained when the diversity index is weighted by the area ratio accounting for the relevance of GDEs in terms of areal extent in the SDL resource unit. The second largest variation in the diversity indices is observed when only moderate to high potential GDEs are considered.

Although not shown here, similar patterns were observed for the Shannon Diversity index.

3.3.2 Calculating the responsiveness metric of the sensitivity index

The responsiveness metric was calculated for all 19 SDLs accounting for the main 8 alluvial aquifers, using data reported in groundwater resource description reports used to support Water Sharing Plans, Groundwater Report Cards, groundwater modelling reports, or a digital product describing the depth of regolith when data on alluvial formations was not available (see Appendix A.2) (MDBA, 2020; NSW DPI, 2018c, 2018b, 2018a, 2019a, 2019b; NSW DPIE, 2019; DNRME, 2018; McNeil et al., 2018; OGIA, 2016; Water, 2015; Welsh et al., 2014; Wilford et al., 2018). See Appendix A.2 for details on the calculation.

In calculating the responsiveness metric, we have also included the Border Rivers Alluvial system in Queensland and New South Wales (GS31, GS33 and GS54, see Table 1). Figure 9 shows the responsiveness metric calculated for all 19 groundwater SDLs and the Border River alluvial system, totalling 22 groundwater SDL resource units. In the responsiveness metric, a high level of recharge relative to storage suggests higher sensitivity as there will be minimal buffering capacity in the aquifer to absorb changes in recharge, whereas lower sensitivity will be observed in the opposite situation (Currie et al., 2010). Higher responsiveness is therefore associated with small alluvial aquifers (or SDL resource units) such as the Upper Macquarie Alluvium (GS45), Upper Gwydir Alluvium (GS43) and Namoi Tributary Alluvium (GS48) SDLs, whereas lower responsiveness is associated with larger alluvial systems (e.g., Lower Murray Deep Alluvium (GS27b), Lower Lachlan Alluvium (GS25)).

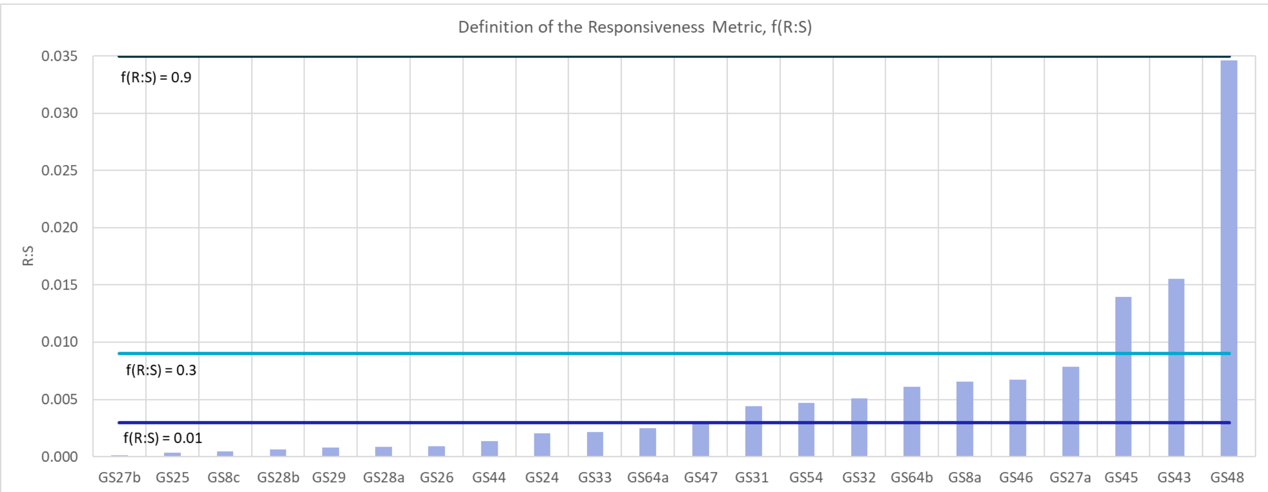

Figure 9 Responsiveness metric f(R:S) calculated for the alluvial aquifers of the MDB

3.3.3 Prioritisation of alluvial aquifers in the MDB

A preliminary analysis indicated that the final aquifer priority ratings, as well as the importance and sensitivity indices, were insensitive to alternative statistics for the groundwater use such as the median, maximum or minimum values for the period with metered data (2012-2019) (see Table 1). Therefore hereafter we present results obtained using the average metered groundwater use in SDLs reported in the Transition Water Take Reports (2012-13/2018-19) (MDBA, 2020b).

Similarly, both diversity indices (Shannon and Simpson Diversity Indices) used to account for the occurrence of GDEs in the importance index, produced no differences in the priority ratings of the alluvial aquifers of the MDB. Therefore, hereafter we discuss results for the Simpson Diversity index only.

When weighting the GDE diversity indices by the GDE area (D vs DA) or the moderate to high potential GDE area (DA vs DAf), discrepancies arise in the importance ratings. For instance, the importance rating for GS8c (Goulburn-Murray: Sedimentary Plain), GS64a (Upper Condamine Alluvium CCA), GS64b (Upper Condamine Alluvium Tributaries), GS24 (Lower Gwydir Alluvium), show the largest fluctuations in ratings (5, 3, 3 and 3, respectively) when weighing the diversity index by the ratio $Area_{GDE}/Area_{SDL}$. This is expected as these SDLs have less than 8% of the total SDL area defined as GDEs in the GDE Atlas. At the same time, more variability is observed in the resulting *f(GDE)* metric when weighting the diversity index by the GDE areas (DA) (Figure 8). Similarly, when the diversity index is weighted by the GDE areas of moderate to high potential, GS25 (Lower Lachlan Alluvium), GS8c (Goulburn-Murray: Sedimentary Plain), GS8a (Goulburn-Murray: Shepparton Irrigation Region), and GS26 (Lower Macquarie Alluvium) show the largest fluctuations (7, 4, 3, 3 and 3, respectively). These SDLs show the largest variations between unweighted and weighted diversity indices in Figure 8, and therefore it is anticipated these discrepancies will impact the importance rating. It is worth noting that these discrepancies apply to the importance index only, which accounts directly for the role of GDEs.

In terms of alluvial aquifer priorities obtained through equation [9], the discrepancies in the priority ratings by different unweighted and weighted diversity indices are reduced to the range 2-4, thus indicating robust priority ratings. Nonetheless, the SDLs identified in the previous paragraph remain as those showing the most important discrepancies in priority rating.

Figure 10 shows the resulting alluvial aquifer prioritisation, importance and sensitivity ratings for all groundwater SDL units analysed in this report, where the size of the symbols reflect the numerical priority rating (smallest size = priority 1; largest size = priority 22). Panels in this figure show priority, importance and sensitivity ratings using the Simpson Diversity Index (SDI)(D), weighted by GDE area (DA) and filtered to include only moderate and high GDE potential (DAf). This figure shows the ordination approach defined as coloured regions in the panels of Figure 10, i.e., blue region: high importance and low sensitivity; green region: high sensitivity and low importance; and yellow region: high importance and high sensitivity. We have defined the top ten SDLs as cut-off value to define important, sensitive and priority aquifers.

In terms of sensitivity ratings, the most sensitive alluvial aquifer system is the Upper Macquarie (GS45) given the high f(R:S) ratio (0.9), indicating high sensitivity to changes in groundwater recharge rates relative to storage, and a metered average annual groundwater use (16,643 ML/y) that closely approaches the SDL value of 17,900 ML/y. Other sensitive alluvial systems included in the top ten ranked aquifers are: Upper Murray Alluvium (GS46), Upper Condamine Alluvium Tributaries (GS64b), Mid-Murrumbidgee Alluvium (GS31), Upper Namoi Tributary Alluvium (GS48), Upper Gwydir Alluvium (GS43), Goulburn-Murray: SIR (GS8a), Lower Murray Shallow Alluvium (GS27a), and the QLD and NSW Border Rivers Alluvium.

In terms of importance ratings, Goulburn-Murray: Sedimentary Plain (GS8c) and the Shepparton Irrigation Region (GS8a) show the highest rating. This rating however changes when weighting the diversity index (D) by GDE area (DA), positioning Lower Lachlan (GS25) at the top, and Upper Namoi (GS47) in second (Figure 8a and 8b).

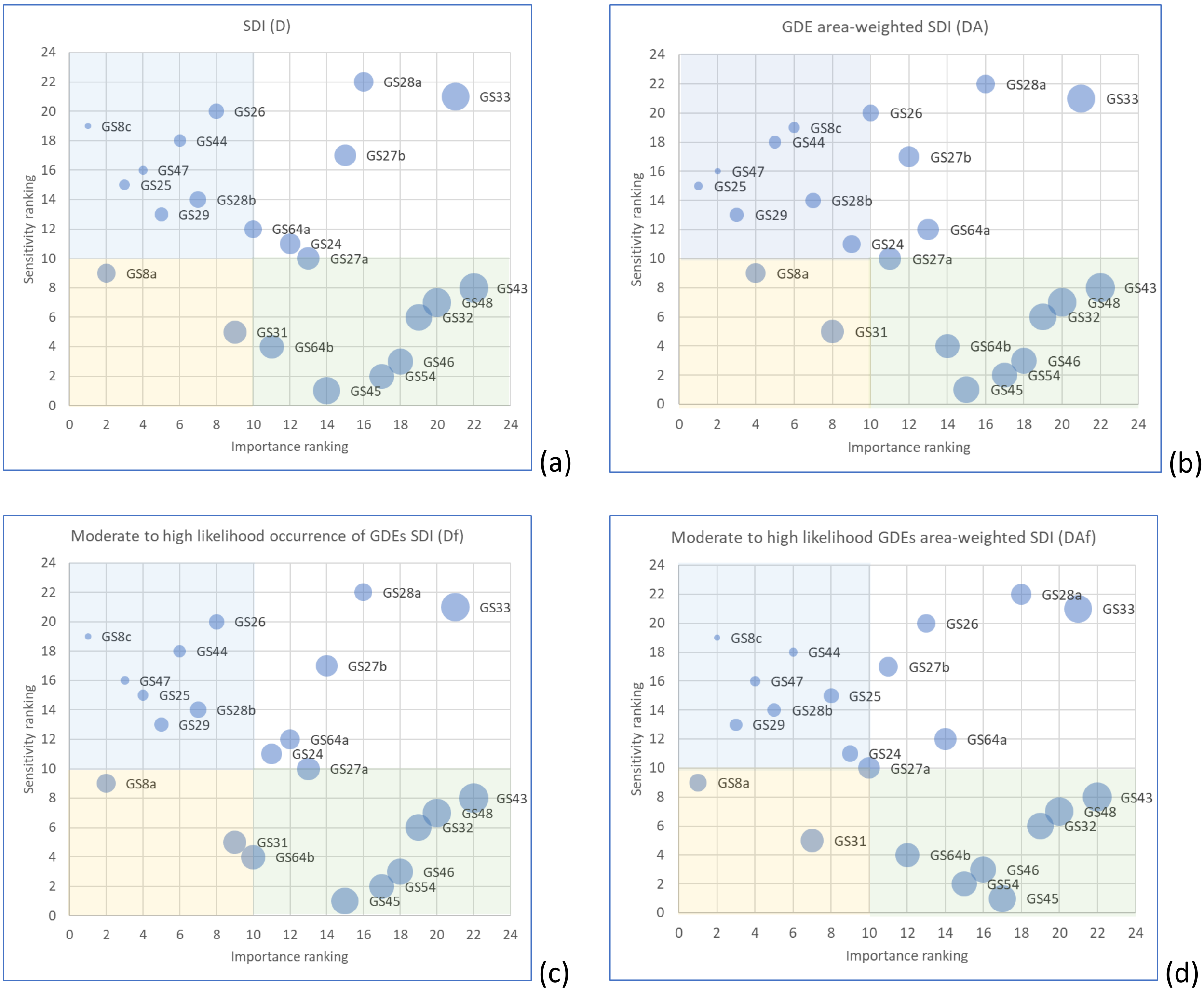

Figure 10 Importance, sensitivity and priority ratings for groundwater SDLs representing the main alluvial aquifers in the MDB. SDI: Simpson Diversity Index. (a) SDI unweighted (D); (b) area-weighted SDI (Da = A_{GDE}/A_{SDL}*D); (c) moderate-to-high potential of GDE SDI (Df); and (d) area-weighted moderate-to-high potential of GDE SDI (Daf = A_{GDE_f}/A_{SDL}*D_f). Size of the bubble represents the priority rating (highest priority indicated by smallest bubble)

This change in priority for the top-rated alluvial aquifers is explained by the large ratio of groundwater extraction of both Lower Lachlan Alluvium (GS25) and Upper Namoi Alluvium (GS47), with respect to the largest groundwater extraction recorded in the alluvial aquifers analysed (e.g. Lower Murrumbidgee Deep Alluvium GS28b), and the significant changes in diversity index values seen in Goulburn-Murray SIR (GS8a) and Goulburn-Murray Sedimentary Plain (GS8c) when weighting the diversity index by GDE area.

Figure 10 also shows that the importance rating dominates the final priority rating whereas the sensitivity rating has limited impact on the final priority rating.

Table 8 shows the results from the ordination approach (Barron et al., 2011; Currie et al., 2010) of alluvial aquifers based on the ratings shown in Figure 10. Considering the top ten ranked alluvial aquifers for both importance and sensitivity, 2 priority alluvial aquifers (Goulburn-Murray: SIR GS8a and Mid-Murrumbidgee Alluvium GS31) were identified as having high importance and high sensitivity consistently across the methods shown in Figure 10.

Table 8 Ordination approach to determine priority of alluvial aquifers in the MDB

High importance – High sensitivity	High importance – Low sensitivity	High sensitivity – Low importance	Low importance – Low sensitivity
GS8a Goulburn-Murray: Shepparton Irrigation Region	**GS8c Goulburn-Murray: Sedimentary Plain**	GS45 Upper Macquarie Alluvium	GS33 NSW Border Rivers Tributary Alluvium
GS31 Mid-Murrumbidgee Alluvium	**GS25 Lower Lachlan Alluvium**	GS54 Queensland Border Rivers Alluvium	GS28a Lower Murrumbidgee Shallow Alluvium
	GS47 Upper Namoi Alluvium	GS46 Upper Murray Alluvium	GS27b Lower Murray Deep Alluvium
	GS29 Lower Namoi Alluvium	GS64b Upper Condamine Alluvium (Tributaries)	GS64a Upper Condamine Alluvium (CCA) (*)
	GS44 Upper Lachlan Alluvium	GS32 NSW Border Rivers Alluvium	GS24 Lower Gwydir Alluvium (*)
	GS28b Lower Murrumbidgee Deep Alluvium	GS48 Upper Namoi Alluvium Tributaries	
	GS26 Lower Macquarie Alluvium	GS43 Upper Gwydir Alluvium	
	GS24 Lower Gwydir Alluvium (*)	GS27a Lower Murray Shallow Alluvium	
	GS64a Upper Condamine Alluvium (CCA) (*)		

(*) Both GS24 (Lower Gwydir) and GS64a (Upper Condamine, CCA) are ranked in the boundary area between low and high importance

Alluvial aquifers supporting irrigated agriculture are identified as of high importance and low sensitivity in Table 8, e.g., Upper and Lower Namoi Alluvium (GS47 and GS29), Upper and Lower Lachlan Alluvium (GS44 and GS25), Lower Murrumbidgee Deep Alluvium (GS28b), and Lower Macquarie Alluvium (GS26). Also, the Goulburn-Murray: Sedimentary Plain (GS8c) is identified as of high importance and low sensitivity. Both Lower Gwydir Alluvium (GS24) and Upper Condamine Alluvium (CCA) (GS64a) sit in the fringe between high and low importance rating.

3.4 Groundwater footprint of alluvial aquifers of the MDB

The groundwater footprint (GF) allows assessing inputs and outputs to aquifers in a single metric to define an index of groundwater stress (Gleeson et al., 2012; Kourgialas et al., 2018; Mahdavi, 2021). Conceptually, the GF represents the ratio between water balance components reflecting outputs/inputs for a given area (A) (aquifer of interest or management unit). If the ratio GF/A > 1, it can then be suggested that the aquifer system is under stress as outputs would be larger than the inputs, thus highlighting unsustainable groundwater use.

Table 4 shows the calculation of the groundwater footprint and the groundwater stress metric defined as GF/A for the alluvial aquifers of the MDB analysed in this report (GF/A > 1.0, alluvial aquifers under stress). Ratios of GF/A indicate groundwater stress for Lower Namoi (GS29), Upper Macquarie Alluvium (GS45) and Upper Namoi Alluvium (GS47) in order of relevance. At the same time, Lower Lachlan Alluvium (GS25) and Lower Gwydir Alluvium (GS24) show GF/A ratios greater than 0.8, thus indicating that main output terms of the groundwater balance are in close proximity to main inputs to the system.

In order to account for limitations imposed in groundwater use due to groundwater salinity we used the iGF as defined in Section 3.2.1. The iGF metric was adapted to account for areas with different salinity classes as defined in the RRAM (MDBA, 2020a) in order to calculate the groundwater footprint considering restrictions due to groundwater quality issues. Considering the calculation of the iGF for different salinity classes allowed updating the groundwater stress metric for each alluvial aquifer. The main assumption for this analysis is that areas of increased salinity are not available for immediate consumptive use thus increasing the level of groundwater stress for a specific SDL area. Similarly, analysing the groundwater footprint metric for different salinity classes might provide insights about the pressure on groundwater resources when considering other than freshwater for consumptive use (e.g., brackish groundwater).

Table 9 Calculation of the groundwater footprint/stress (Gleeson et al., 2012) **for alluvial aquifers of the MDB**

SDL code	SDL resource unit	Average Annual Actual GW Take (ML/y) 2012-2019 (C)	Recharge (ML/y) (R)	Area (km²) (A)	GW discharge to streams (ML/y) (E)	GF (km²)	Groundwater Stress (GF/A)	References/notes to estimate E
GS29	Lower Namoi Alluvium	89457.1	68200	7115.1	600	9415.6	1.323	MDBA (2020), MDBA (2020b)
GS45	Upper Macquarie Alluvium	16642.9	20600	273.2	7510	347.3	1.271	MDBA (2020), MDBA (2020b)
GS47	Upper Namoi Alluvium	98257.1	91000	3573	7510	4205	1.177	MDBA (2020), MDBA (2020b)
GS25	Lower Lachlan Alluvium	108642.9	120000	25282.6	500	22985.6	0.909	NSW DPI (2018b), MDBA (2020b)
GS24	Lower Gwydir Alluvium	35900	47100	2340.4	3400	1922.7	0.822	MDBA (2020), MDBA (2020b)
GS28b	Lower Murrumbidgee Deep Alluvium	261600	411100	32437.9	1500	20717.2	0.639	MDBA (2020), MDBA (2020b)
GS46	Upper Murray Alluvium	12075.7	19700	489.4	0	300	0.613	MDBA (2020b)
GS31	Mid-Murrumbidgee Alluvium	38957.1	73200	1472.7	5780	851	0.578	NSW-DPIE (2019b), MDBA (2020b)
GS26	Lower Macquarie Alluvium	32942.9	62800	3961	5200	2265.4	0.572	MDBA (2020), MDBA (2020b)
GS8c	Goulburn-Murray: Sedimentary Plain	126642.9	450200	21928.9	153548.8	9361.6	0.427	Q95 at gauging stations 403241 (Ovens River at Peechelba), 402205 (Kiewa River at Bandiana), 401230 (Corryong Creek at Towong), 401229 (Cudgewa Creek at Cudgewa North), 404204 (Boosey Creek at Tungamah), 405269 (Seven Creeks at Kialla West), 405226 (Pranjip Creek at Moorilim), 407290 (Bullock Creek at East Loddon), 407236 (Mount Hope Creek at Mitiamo), 407205 (Loddon River at Appin South). Selection of these stations is based on gaining river sections identified in VIC-DELWP (2020), MDBA (2020b)
GS64b	Upper Condamine Alluvium (Tributaries)	33157.1	84000	3777.7	39.6	1491.9	0.395	MDBA (2020), MDBA (2020b)
GS64a	Upper Condamine Alluvium (Central Condamine Alluvium)	46671.4	128000	4346	60.4	1585.4	0.365	MDBA (2020), MDBA (2020b)
GS44	Upper Lachlan Alluvium	57442.9	186500	12962.7	5270	4108.7	0.317	Q95 at gauging station 412006 (Condonlin Bridge), MDBA (2020b)
GS32	NSW Border Rivers Alluvium	5221.4	19000	366	835.7	105.2	0.287	NSW-DPIE (2019), MDBA (2020b)
GS27b	Lower Murray Deep Alluvium	68671.4	271000	17803.2	6200	4616.9	0.259	MDBA (2020), MDBA (2020b)
GS54	Queensland Border Rivers Alluvium	11992.9	68500	2042.2	0	357.6	0.175	Welsh et al. (2014), MDBA (2020b)
GS8a	Goulburn-Murray: Shepparton Irrigation Region	56271.4	498000	6579.9	142763.5	1042.3	0.158	Q95 at gauging station 405232 (Goulburn River at McCoys Bridge) and 406265 (Campaspe River at Echuca)
GS48	Upper Namoi Tributary Alluvium	288.6	2360	56.4	0	6.9	0.122	MDBA (2020b)
GS33	NSW Border Rivers Tributary Alluvium	167.1	4500	248.6	197.9	9.7	0.039	NSW-DPIE (2019), MDBA (2020b)
GS27a	Lower Murray Shallow Alluvium	6274.3	337000	17803.2	6200	337.7	0.019	MDBA (2020), MDBA (2020b)
GS28a	Lower Murrumbidgee Shallow Alluvium	6862.9	438000	32437.9	1500	510	0.016	MDBA (2020), MDBA (2020b)
GS43	Upper Gwydir Alluvium	77.1	7500	97.4	556.7	1.1	0.011	Q95 at gauging stations 418013 (Gwydir River at Gravesend Road Bridge) and 418012 (Gwydir River at Pinegrove) probably influenced by dam streamflow regulation. E is calculated as a fraction of recharge, where fraction is defined as the ratio Q90/Qavg (Gleeson et al., 2012), MDBA (2020b)

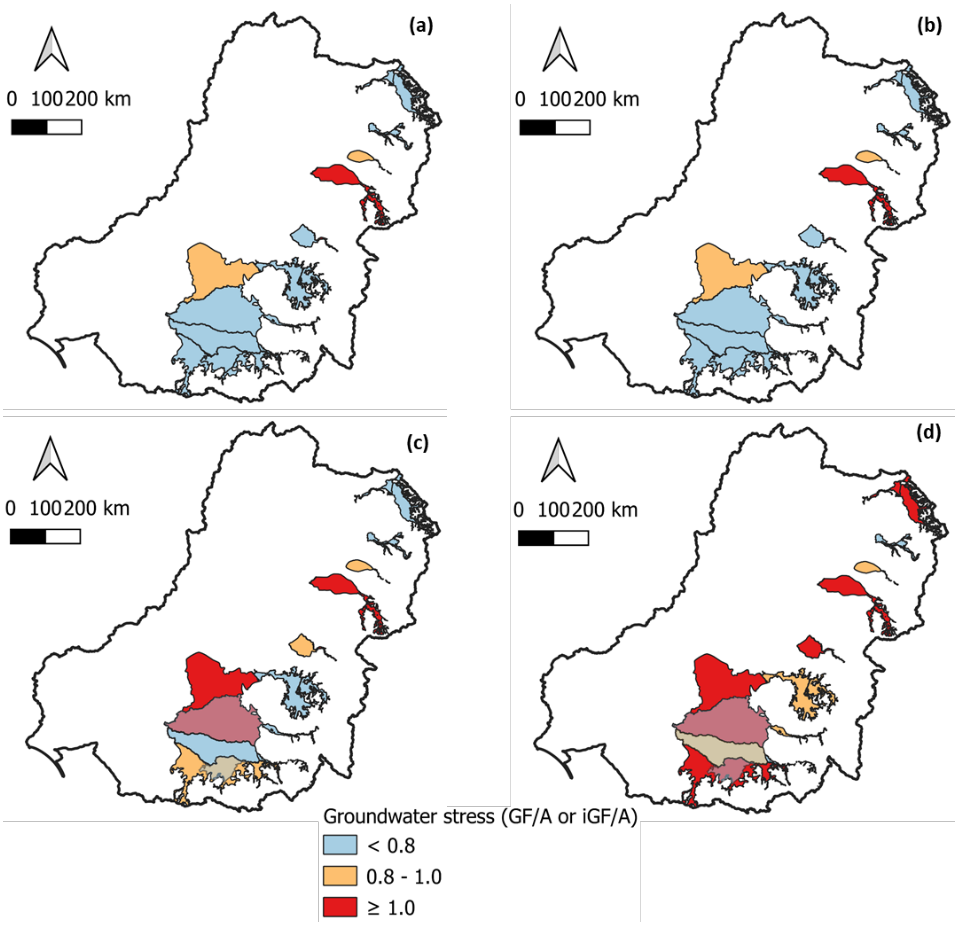

Figure 11 Groundwater stress expressed as (a) GF/A and (b-d) iGF/A when considering (b) salinity class 4 (>14,000 mg/L), (c) salinity class 3 (3,000-14,000 mg/L), and (d) salinity class 2 (1,500-3,000 mg/L)

Figure 11 shows the GF/A and iGF/A values for salinity classes 4 (highly saline, >14,000 mg/L TDS), 3 (saline, 3,000-14,000 mg/L TDS) and 2 (brackish, 1,500-3,000 mg/L TDS) as defined in Table 5. Figure 11a shows the groundwater stress metric (GF/A) with no account for the salinity values and represents results obtained in Table 8, where Namoi alluvium (GS29 and GS47) and Upper Macquarie Alluvium (GS47) are highlighted under stress, and Lower Gwydir Alluvium (GS24) and Lower Lachlan Alluvium (GS25) are highlighted with values greater than 0.8 for the stress metric. This stress metric thus relates only to groundwater quantity assessment and can be regarded as a baseline for comparison.

Figure 11b accounts for areas defined as highly saline from the interpolation scheme described in section 3.2.1. These areas are observed in the Lower Murray Deep Alluvium (GS27b) and both Goulburn-Murray SDLs (GS8a and GS8c), and account for a maximum of 15% of the total area in the case of GS8c. For these SDLs however these highly saline areas are not extensive enough to move the groundwater stress metric (iGF) to values above 1.0 (Figure 11b) and no changes with respect to the baseline (panel a) are observed.

When considering areas defined as saline groundwater (Figure 11c) some changes in the groundwater stress metric (iGF) are observed with respect to the baseline (GF/A). Both Lower Lachlan Alluvium (GS25) and Lower Murrumbidgee Deep Alluvium (GS28b) move into groundwater stress given the increase in areas falling under this salinity class (57% and 48% of total SDL area, respectively). At the same time, Lower Gwydir Alluvium (GS24), Lower Macquarie Alluvium (GS26), and Goulburn-Murray: Sedimentary Plan (GS8c) are highlighted with values greater than 0.8 for the stress metric (iGF).

Finally, when considering a more restrictive situation suggesting brackish groundwater is not available for consumptive use (Figure 11d) few SDLs are added to the previous pool of unsustainable groundwater use (iGF/A > 1.0): Lower Macquarie Alluvium (GS26), Upper Condamine Alluvium (CCA) (GS64a), Upper Condamine Alluvium Tributaries (GS64b) and Goulburn-Murray: Sedimentary Plan (GS8c). Similarly, Lower Murray Deep Alluvium (GS27b), Mid-Murrumbidgee Alluvium (GS31) and Upper Lachlan Alluvium (GS44) show values greater than 0.8 for the stress metric (iGF).

Table 9 summarises these results highlighting the new SDLs under groundwater stress added for each corresponding salinity class with respect to the previous class.

Table 10 SDLs showing unsustainable groundwater use based on the groundwater quantity footprint metric (GF) and groundwater quality footprint metric (iGF)

GF/A	iGF/A (Class 4 – Highly Saline)	iGF/A (Class 3 – Saline)	iGF/A (Class 2 – Brackish)
Lower Namoi Alluvium (GS29)	Lower Namoi Alluvium (GS29)	**Lower Lachlan Alluvium (GS25)**	Lower Lachlan Alluvium (GS25)
Upper Macquarie Alluvium (GS45)	Upper Macquarie Alluvium (GS45)	**Lower Murrumbidgee Deep Alluvium (GS28b)**	**Lower Macquarie Alluvium (GS26)**
Upper Namoi Alluvium (GS47)	Upper Namoi Alluvium (GS47)	Lower Namoi Alluvium (GS29)	Lower Murrumbidgee Deep Alluvium (GS28b)
		Upper Macquarie Alluvium (GS45)	Lower Namoi Alluvium (GS29)
		Upper Namoi Alluvium (GS47)	Upper Macquarie Alluvium (GS45)
			Upper Namoi Alluvium (GS47)
			Upper Condamine Alluvium (Central Condamine Alluvium) (GS64a)
			Upper Condamine Alluvium (Tributaries) (GS64b)
			Goulburn-Murray: Sedimentary Plain (GS8c)

4 Concluding remarks and next steps

Groundwater use in the Murray-Darling Basin concentrates in major alluvial aquifers of the basin. Nearly 75% [70%-80%] of the metered groundwater use in the basin for the period 2012-2019 concentrates in 8 alluvial aquifers. These 8 alluvial systems correspond to 19 groundwater SDL resource units (as defined in the Basin Plan), with an average metered consumption of 1114 GL/y, ranging between 834 GL/y and 1502 GL/y for the period 2012-2019[3]. Out of this average metered consumptive use and at basin-state level New South Wales, Victoria and Queensland concentrate 75% [66%-79%], 17% [13%-23%] and 8% [7%-11%], respectively.

Based on the trend analysis performed at SDL scale on the mean depth-to-water table (DTW) values recorded across 910 observation bores, the ordination approach to group SDL resource units in terms of importance, sensitivity and priority, and metrics expressing groundwater stress including both quantity and quality aspects, Table 11 shows a summary of indicators describing the situation for each SDL resource unit analysed. These qualitative descriptors relate to: (1) above average increasing trends for mean annual DTW, (2) ordination approach based on high importance–high sensitivity or high importance–low sensitivity alluvial aquifers, and (3) groundwater stress metric based on quantity only (GF/A) or groundwater stress metric considering Salinity Class 3 (iGF/A). The latter assumes brackish and fresh groundwater are available for consumptive use for the calculation of the groundwater stress metric. The 3 qualitative descriptors employed are regarded as equally relevant when integrating across different SDLs in the next paragraph.

From Table 11 we observe that 9 SDLs, namely, Lower Gwydir Alluvium (GS24), Lower Murrumbidgee Deep Alluvium (GS28b), Lower Namoi Alluvium (GS29), Mid-Murrumbidgee Alluvium (GS31), Upper Macquarie Alluvium (GS45), Upper Namoi Alluvium (GS47), Upper Condamine Alluvium (CCA) (GS64a), Goulburn-Murray: Shepparton Irrigation Region (GS8a) and Goulburn-Murray: Sedimentary Plain (GS8c) show strong indication of the presence of the qualitative descriptors in at least one aspect analysed. Out of this group it seems critical to address potential groundwater sustainability issues in the Lower and Upper Namoi Alluvium (GS29 and GS47), and in the Mid-Murrumbidgee Alluvium (GS31), as they both show strong indication of the presence of a qualitative descriptor in at least 2 aspects. Similarly, Lower Lachlan Alluvium (GS25) and Lower Murrumbidgee Deep Alluvium (GS28b) are highlighted as high importance–low sensitivity and show signs of groundwater stress when considering aspects of groundwater quality.

[3] For completeness of analysis these figures include the metered groundwater use reported for the Border Rivers Alluvium SDLs: GS32, GS33 and GS54)

Table 11 Summary of qualitative descriptors related to trends in DTW, priority concept and groundwater stress for the SDL units analysed.

SDL code	SDL resource unit	Increasing DTW trend above average	High importance or High importance-low sensitivity	Groundwater stress quantity and quality
GS24	Lower Gwydir Alluvium	☑(*)	✓(**)	
GS25	Lower Lachlan Alluvium		✓	✓
GS26	Lower Macquarie Alluvium		✓	
GS27a	Lower Murray Shallow Alluvium			
GS27b	Lower Murray Deep Alluvium			
GS28a	Lower Murrumbidgee Shallow Alluvium			
GS28b	Lower Murrumbidgee Deep Alluvium	☑	✓	✓
GS29	Lower Namoi Alluvium	☑	✓	☑
GS31	Mid-Murrumbidgee Alluvium	☑	☑	
GS32	NSW Border Rivers Alluvium			
GS33	NSW Border Rivers Tributary Alluvium			
GS43	Upper Gwydir Alluvium			
GS44	Upper Lachlan Alluvium		✓	
GS45	Upper Macquarie Alluvium			☑
GS46	Upper Murray Alluvium			
GS47	Upper Namoi Alluvium	☑	✓	☑
GS48	Upper Namoi Tributary Alluvium			
GS54	Queensland Border Rivers Alluvium			
GS64a	Upper Condamine Alluvium (Central Condamine Alluvium)	☑	✓	
GS64b	Upper Condamine Alluvium (Tributaries)			
GS8a	Goulburn-Murray: Shepparton Irrigation Region		☑	
GS8c	Goulburn-Murray: Sedimentary Plain	☑	✓	

(*) tick-in-a-box = strong indication of qualitative descriptor
(**) tick = secondary indication of qualitative descriptor, e.g. high-importance and low sensitivity; iGF/A for Salinity Class 3 (Saline)

Results from the groundwater level trend analysis, aquifer prioritisation and groundwater footprint work have provided insights into spatial and temporal patterns of groundwater dynamics and processes, groundwater salinity, recharge and extraction patterns, and groundwater resource stress and hotspots. Next steps will focus on exploring opportunities and options to help address potential water management problems in SDL resource units identified through the trend analysis and prioritisation work. In 2022/23 we will conduct assessments of potential opportunities to augment water security through the principles of conjunctive water management and integrated water resource management. This includes active management options such as managed aquifer recharge and groundwater desalination as well as identifying potential restrictions or research gaps in terms of management/regulation aspects for effective water management. We propose to consolidate the deliverables identified in the Research Implementation Plan (RIP) into one report and/or scientific article detailing the opportunities for groundwater as an adaptation to current water resources management.

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Appendices

A.1 Standardisation process to obtain importance index

This standardisation process ensures that both importance and sensitivity indices are given equivalent numerical weighting before being combined. As both indices have a different number of individual metrics in their respective calculations, which span different orders of magnitude, this standardisation corrects for this inequality. The procedure considers the following calculations (Barron et al., 2011; Currie et al., 2010):

$$I_L = log_{10}\left(\frac{I}{I_{max}}\right) \qquad [A.1]$$

$$Se_L = log_{10}\left(\frac{Se}{Se_{max}}\right) \qquad [A.2]$$

$$Se_{alt} = \frac{Se_L[min(Se_L) - min(I_L)]}{min(Se_L)} \qquad [A.3]$$

$$Se_{standardized} = 10^{Se_{alt}} \qquad [A.4]$$

$$Final\ Prioritization = \frac{I}{I_{max}} * Se_{standardized} \qquad [A.5]$$

where I is the importance score, I_{max} is the maximum importance score in the dataset, Se is the sensitivity score, Se_{max} is the maximum sensitivity score in the aquifer dataset.

A.2 Calculation of the responsiveness metric

Following Barron et al. (2011) we defined 3 classes for f(R:S) such that the middle-class point between the low class and middle class was 3-fold and 9-fold between low and high class. These classes are defined using the ratios R:S as follows:

Classes for R:S	Middle-point class	Class definition for f(R:S)
0-0.003	0.0015	Low
0.003-0.009	0.0045	Moderate
0.009-0.035	0.014	High

Using these classes, the responsiveness metric was calculated in the following table:

SDL code	SDL name	BDL (GL/y)	SDL (GL/y)	Average Aquifer Storage (ML)	Recharge (ML)	Ratio R:S	f(R:S)
GS64a	Upper Condamine Alluvium (Central Condamine Alluvium)	81.4	46.0	51272524	128000	2.496E-03	0.01
GS33	NSW Border Rivers Tributary Alluvium	0.4	0.4	2091559	4500	2.152E-03	0.01
GS27b	Lower Murray Deep Alluvium	88.9	88.9	2161513567	271000	1.254E-04	0.01
GS28a	Lower Murrumbidgee Shallow Alluvium	26.9	26.9	517822638	438000	8.458E-04	0.01
GS28b	Lower Murrumbidgee Deep Alluvium	273.6	273.6	716322172	438000	6.115E-04	0.01
GS25	Lower Lachlan Alluvium	123.4	117.0	353905243	120000	3.391E-04	0.01
GS44	Upper Lachlan Alluvium	94.2	94.2	138833409	186500	1.343E-03	0.01
GS26	Lower Macquarie Alluvium	70.7	70.7	66642932	62800	9.423E-04	0.01
GS29	Lower Namoi Alluvium	88.3	88.3	86607807	68200	7.875E-04	0.01
GS47	Upper Namoi Alluvium	123.4	123.4	32021543	91000	2.842E-03	0.01
GS24	Lower Gwydir Alluvium	33.0	33.0	23312146	47100	2.020E-03	0.01
GS8c	Goulburn-Murray: Sedimentary Plain	203.5	223.0	926496905	450200	4.859E-04	0.01
GS64b	Upper Condamine Alluvium (Tributaries)	45.5	40.5	13695906	84000	6.133E-03	0.3
GS54	Queensland Border Rivers Alluvium	14.0	14.0	14602053	68500	4.691E-03	0.3
GS32	NSW Border Rivers Alluvium	8.4	8.4	3745195	19000	5.073E-03	0.3
GS27a	Lower Murray Shallow Alluvium	81.9	81.9	42982347	337000	7.840E-03	0.3
GS46	Upper Murray Alluvium	14.1	14.1	2920169	19700	6.746E-03	0.3
GS31	Mid-Murrumbidgee Alluvium	53.5	53.5	16531517	73200	4.428E-03	0.3
GS8a	Goulburn-Murray: Shepparton Irrigation Region	244.1	244.1	75997498	498000	6.553E-03	0.3
GS45	Upper Macquarie Alluvium	17.9	17.9	1478036	20600	1.394E-02	0.9
GS48	Upper Namoi Tributary Alluvium	1.8	1.8	68217	2360	3.460E-02	0.9
GS43	Upper Gwydir Alluvium	0.7	0.7	482393	7500	1.555E-02	0.9

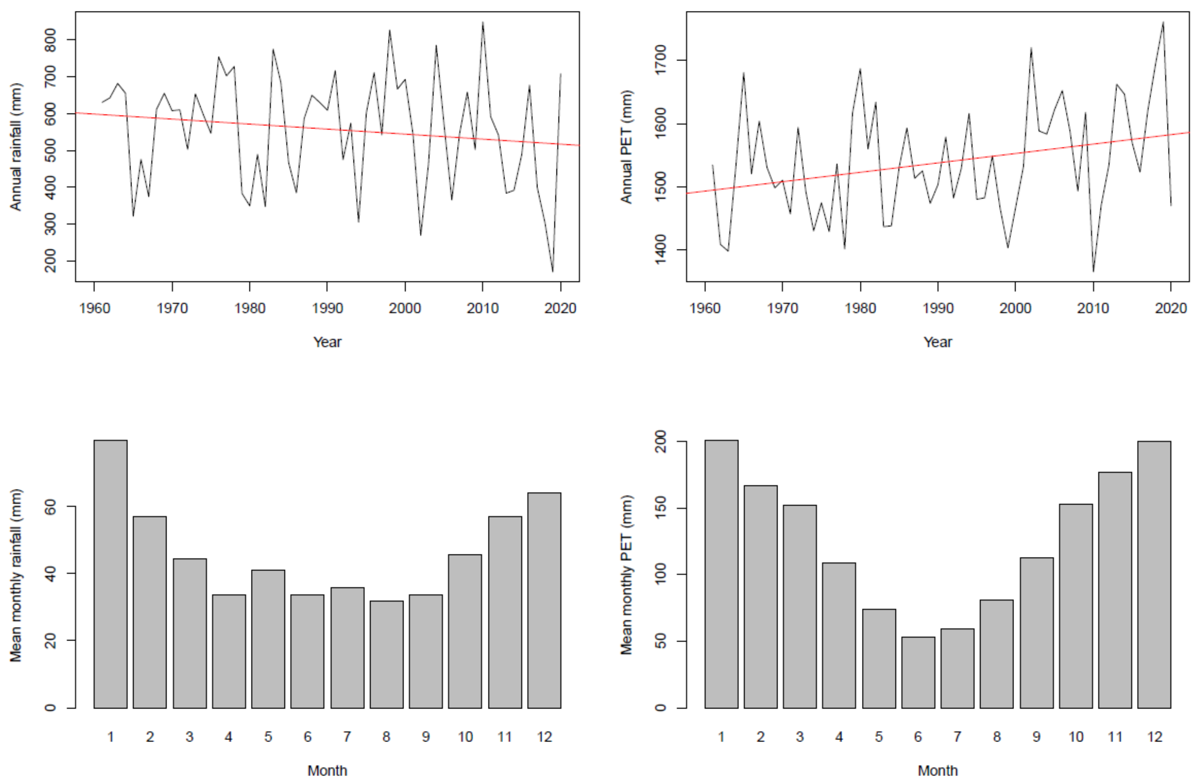
A.3 Analysis of climate data for the main alluvial systems of the MDB

The SILO climate data at 0.05^{o} grid cells for the 8 alluvial systems identified in Section 1.2 (Figure 3) have been downloaded. Exploratory data analysis (EDA) for the period 1960-2020 for all the SILO grid cells contained in the alluvial aquifers identified in section 1.2 is shown in Figure A.1. This analysis indicates that:

- annual rainfall shows a slightly decreasing trend and is dominated with year-to-year and decadal variability;
- potential evapotranspiration (PET), on the contrary, shows an increasing trend;
- rainfall annual cycles vary from summer-rainfall in the northern alluvial systems, to even-distribution in the middle, and then winter-rainfall in the southern alluvial systems.

Figure A.1 Annual and monthly rainfall and PET in 8 alluvial systems of the MDB (from north to south)

Namoi Alluvium



Macquarie Alluvium

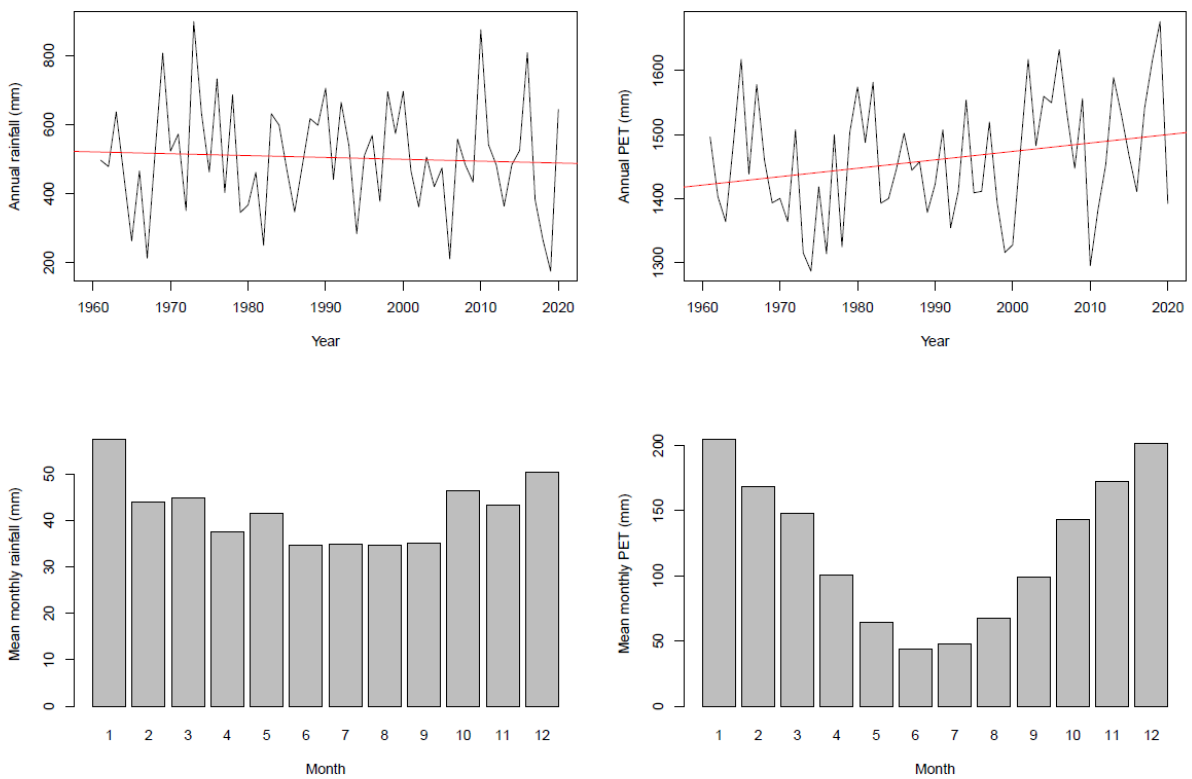
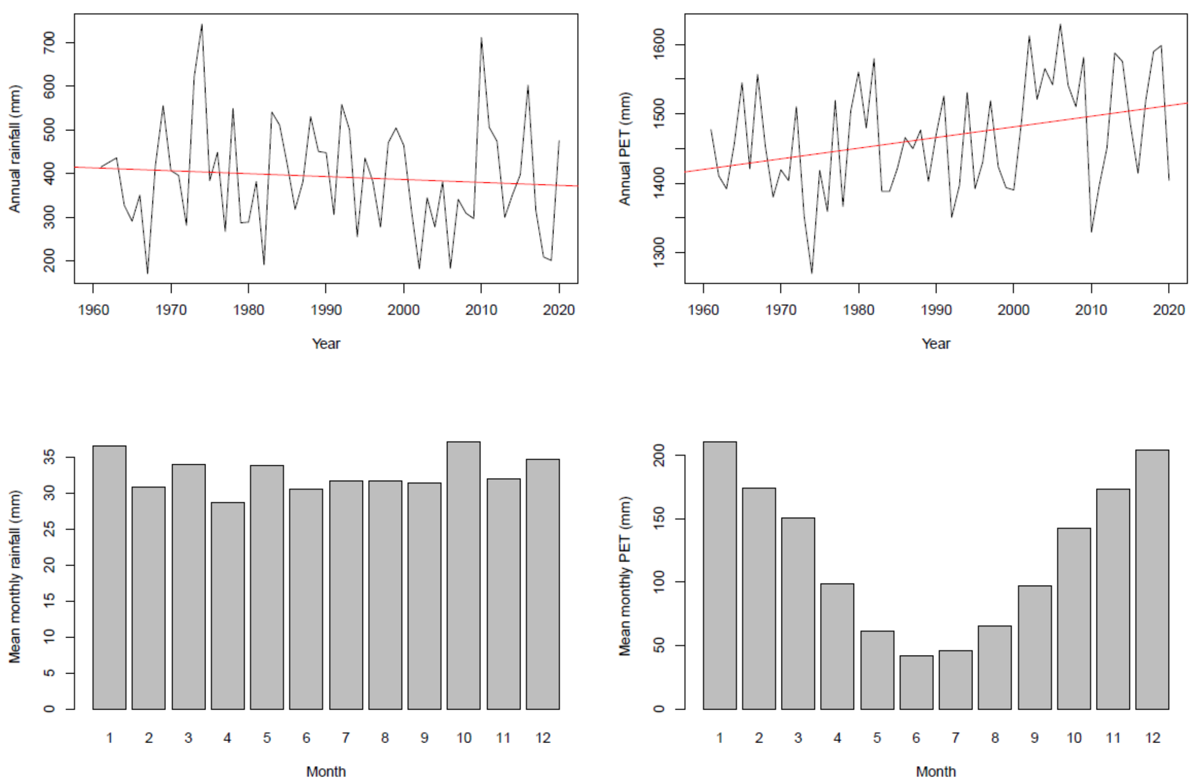


Figure A.1 Cont'd

Lachlan Alluvium



Murrumbidgee Alluvium

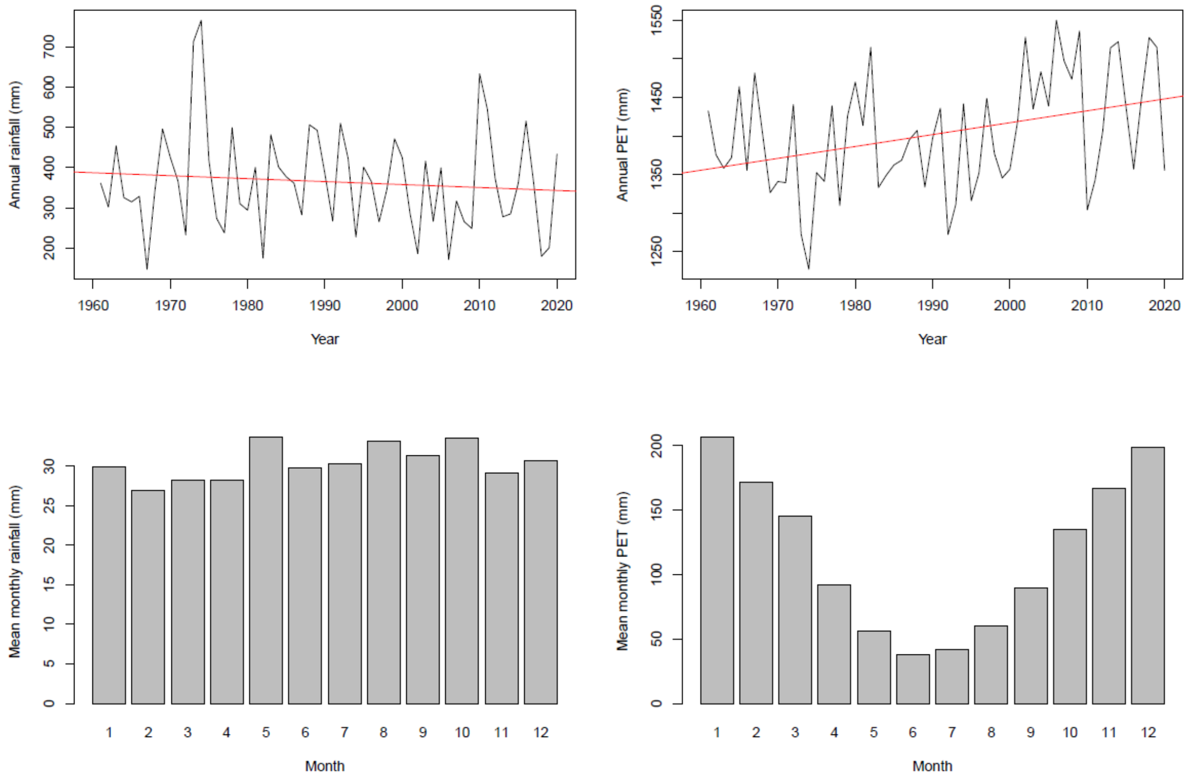


Figure A.1 Cont'd

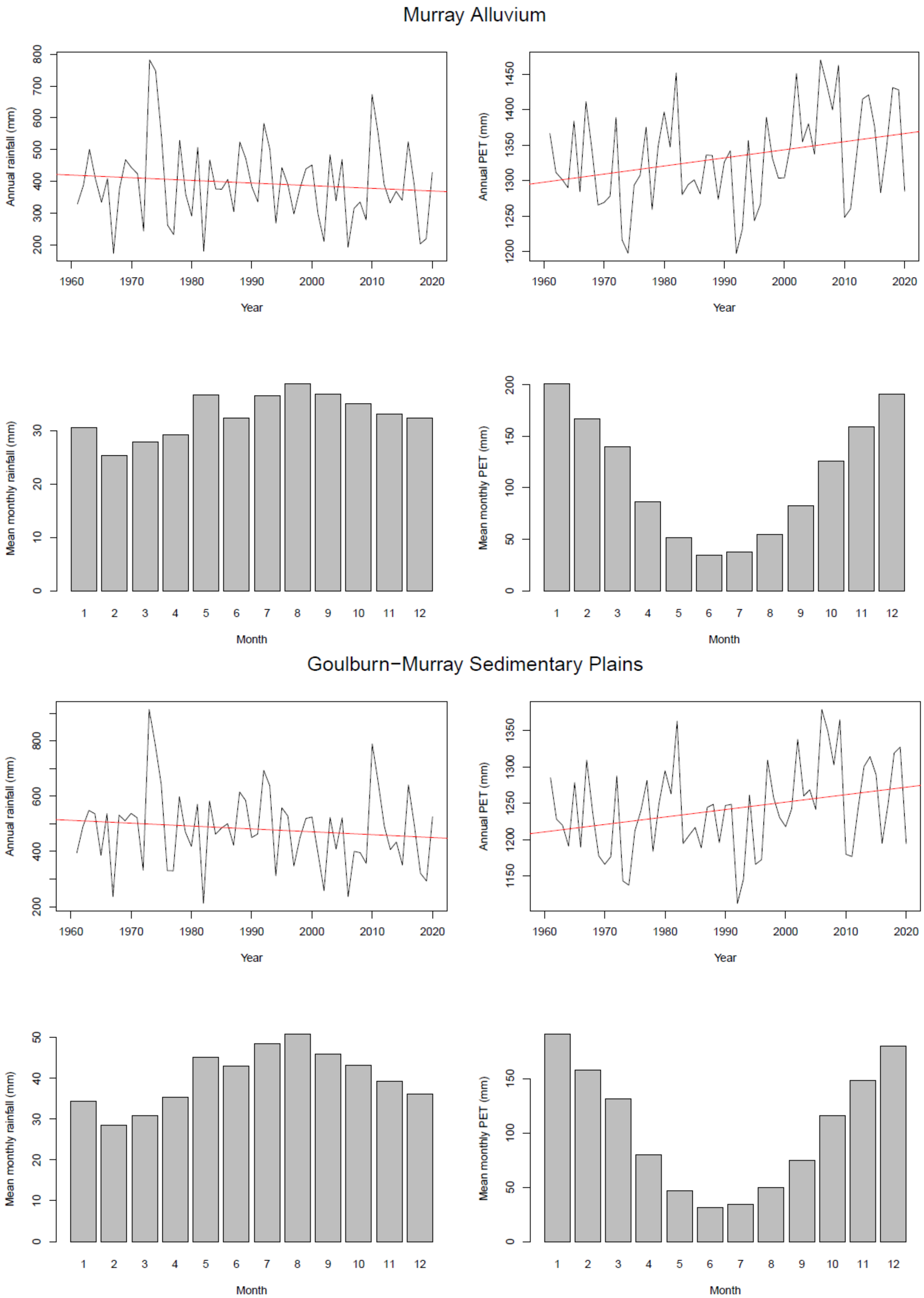


Figure A.1 Cont'd

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